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16. ABSTRACT

This two volume set presents in detail technical design information for the following sludge treatment and disposal processes: lime stabilization, anaerobic digestion, aerobic digestion, thermal sludge conditioning, thickening, dewatering, incineration and pyrolysis, composting, land utilization, and landfilling. The discussion of each process includes, where possible, a presentation of performance data for existing operations as well as operation and maintenance experiences and energy and cost information. Each chapter includes one or more design examples to illustrate step-by-step, the philosophy, rationale, and methodology behind the design of the particular process.

The goal of processing and treatment research and development is to produce technology alternatives which can be used to prepare the sludge for application to the land or for one of the conversion processes so that the total cost of handling or disposal is minimized. This publication is the culmination of two years of intensive work and eight seminars that were presented around the nation in an effort to develop and disseminate the latest information in this area.

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Sludge Disposal

Volume 2

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Chapter 7

Incineration-Pyrolysis of Wastewater Treatment Plant Sludges

Sludge disposal is a major consideration in the planning and design of new wastewater treatment plants and in the expansion and upgrading of existing facilities. Along with the increasing sophistication of wastewater treatment comes more sludge and greater disposal problems. Many wastewater treatment facilities have shown that satisfactory treatment and disposal of sludge can be the most complex and costly operation in a municipal wastewater treatment system. A sludge disposal system which reduces the volume of material to be handled and disposed and saves or recovers needed energy and resources is very desirable. If this system is cost-effective, the selection of a sludge disposal system is facilitated for particular communities.

Sewage sludge incineration has been practiced since the early part of the century. This method of sludge disposal was an adaptation of various industrial combustion processes developed during the latter part of the nineteenth century. Availability of cheap energy, limited capability of sludge dewatering equipment, and minimal or nonexistent air pollution requirements all led to the selection of incineration as a practical and inexpensive method of sludge disposal. However, increasing concern for air quality and experience with sludges from more advanced treatment processes, which are more difficult to dewater and, thus, require more energy to evaporate the excess water, considerably dampened the enthusiasm for incineration. These problems, coupled with rising energy costs, increasing quantities of sludge, and limited resources, have led to the development of improved sludge dewatering methods and more efficient incineration equipment and systems.

This chapter describes various sewage sludge incineration systems in the United States and some of the new and promising combustion systems proposed for various facilities. Currently, there are many sludge incineration systems being tried or in use, such as the rotary kiln. However, this paper is limited to the consideration of the following four furnace systems: multiple-hearth, fluid bed, single-hearth cyclonic, and electric. The new combustion systems reviewed are pyrolysis in multiple-hearth furnaces and alternate fuel sources, such as solid waste or coal in conventional combustion processes. While there are many other systems being tested and demonstrated, this paper is limited to the systems which are considered proven technologies. Heat recovery methods used to recover the energy spent in the combustion of sewage sludge are also discussed. Two design examples for combustion of sewage sludge are presented to illustrate the basic methodology of furnace selection and design.

PRINCIPLES OF COMBUSTION

Combustion is the rapid chemical combination of oxygen with the volatile elements of the fuel. The combustible elements that characterize any fuel are carbon, hydrogen, and, in some cases, sulfur. Quantities of sulfur contained in sewage sludge are so low that combustion of sulfur does not significantly contribute to the overall combustion process and thus is not considered in this paper.

Combustion reactions are exothermic and release large amounts of energy as heat. The ideal combustion reactions for carbon and hydrogen are:

$$C + O_2 = CO_2 + 14{,}100 \text{ Btu/lb of C}$$

$$2H_2 + O_2 = 2H_2O + 61{,}100 \text{ Btu/lb of } H_2$$

Air is usually the source of oxygen for combustion, although pure oxygen feed systems have been used in some cases.

The objective of an incineration system is to release heat from a fuel and completely destroy all the volatile elements, while minimizing combustion imperfections and heat losses. Sewage sludge is difficult to combust completely because it is not homogeneous and it contains high levels of inert material and water.

Complete combustion is a result of the proper combination of the combustible elements of the fuel with oxygen. This requires a temperature high enough for ignition of the constituents, good turbulence for contact and mixing, and sufficient time for complete reaction. Since only an ideal system can meet all of these requirements, excess air, greater than the stoichiometric combustion requirement, is provided to assure sufficient oxygen when complete combustion is desired. In typical sewage sludge incinerators, excess air quantities vary upward from 30 percent and may exceed 150 percent, depending upon the type of furnace used and the method of operation. This excess air leaves the system at the stack exhaust temperature, and the heat used to raise ambient air to stack temperature is a severe heat loss from the system. Thus, it is desirable to keep the excess air at a minimum to reduce stack heat losses.

Pyrolysis is defined as: gasification and/or liquification of the combustible elements by heat in the total absence of oxygen. Partial pyrolysis, or more correctly, starved-air combustion, can be defined as: gasification of the combustible elements by heat in the presence of controlled amounts of oxygen. Partial pyrolysis uses less than the stoichiometric combustion air requirements. The ash from a pyrolysis reaction contains combustible material and some fixed carbon which was not volatilized during combustion. The gas, also called fuel gas, from the pyrolysis reactor consists of various combustible gases, such as carbon monoxide, methane, ethylene, and some higher hydrocarbons, and appreciable quantities of carbon dioxide and water vapor. Small quantities of hydrogen, oxygen, and nitrogen are sometimes present. The yield and composition of the pyrolysis products are dependent upon several variables; the interrelationships of these are so complex that predicting final product characteristics is a difficult task and is determined empirically.

ENERGY RECOVERY

Energy conservation is a great concern of industries and municipalities. Costs are rising for both fossil fuel and electric power. This cost consideration, coupled with increasing air quality requirements, has led to the development of new, more efficient incineration processes, alternate fuel sources, and new ways to recover energy and limit energy losses.

Combustion energy losses are generally due to radiation, leakage, ash and stack loss, with the greatest heat loss being stack loss. Much of the stack loss can be recovered by heat recovery systems. Heat recovery systems can be applied to any hot gases, but system economics must be reviewed to determine their feasibility in the particular application. The San Francisco Bay Area Air Pollution Control District (SFBAAPCD) requires furnace exhaust temperatures high enough to prevent carryover of unburned hydrocarbons. This requirement is satisfied by maintaining a temperature of 1400°F for one-half second. This high exhaust gas temperature requirement is becoming more common throughout the country. Some form of waste heat recovery should be considered for all projects with similar constraints.

There are three basic transfer methods used to recover heat from stack exhaust: gas-to-water, gas-to-air, and gas-to-organic fluid. Gas-to-water systems produce steam and are the most commonly used heat recovery systems. Steam has a tremendous heat energy per unit weight. Gas-to-air systems generally use recuperators or air heaters to preheat incoming combustion air. Research is underway on gas-to-air waste heat recovery where heated air is used for power generation. Gas-to-organic fluid systems have the advantage of high temperature with low pressures resulting in low installation and operation costs and are used in industrial plant processes. Use of this type of system has increased markedly over the past several years. Fluids used for this system include mineral oil and ethylene glycol. This technology has not been used in wastewater treatment facilities because of the low number of heat-demanding or shedding processes as compared to industry.

Minimizing the other heat losses, radiation, ash and leakage, should be economically evaluated. Proper insulation is important for personal comfort and safety and minimizing radiation losses. When safety concerns have been alleviated, the amount of additional insulation is an economic consideration. Leakage must be minimized for safety reasons and is usually not a major loss in a well-constructed furnace. Heat lost to the ash can be due to temperature and/or unburned combustibles. Unburned material can be reduced by process control or by using the ash as a filter aid and returning it to the furnace. The temperature of the ash can be used to preheat boiler makeup water or to satisfy other low volume heat demands.

Selection of a system that will recover the maximum available heat with the highest transfer efficiency and lowest cost is a challenging engineering problem. The selection requires a complete system review. Typical system components and processes reviewed include: the furnace, the gas collection and removal equipment, combustion air supply, combustion products (gas and ash), waste heat boiler, refractories, insulation, baffles, supplemental air and water systems, boiler feedwater, boiler feedwater treatment, boiler blowdown, boiler trim, steam separation, foundations, supports, breeching, exhaust gas scrubbers, etc.

A complex waste heat recovery boiler system is shown on figure 7–1. A typical sewage sludge furnace heat recovery system would only require the evaporation section of the boiler with some feedwater conditioning. To properly design any heat recovery system, consideration of the following parameters is required:

- Chemical nature, temperature, and corrosiveness of the exhaust gases.
- Quantity, specific gravity, size and nature of the fly ash.
- Available draft.
- Type of exhaust gas system (pressure or vacuum).
- Space available.
- Requirements for supplemental firing for: start-up, preheating, emergency use, stabilizing furnace conditions or other uses.
- Present and future steam demands.
- Type of demand (continuous or intermittent).
- Equipment redundancy requirements.
- Other special requirements of the individual process.

The waste heat boiler alone requires a review of: materials of construction; type of design, fired or unfired; type of tubes, bare or fin; type of circulation, natural- or forced-air; number of passes, superheater requirements, economizer requirements, ash removal and disposal system, steam pressure and temperature, degree of feedwater treatment, methods of feedwater treatment, chemical

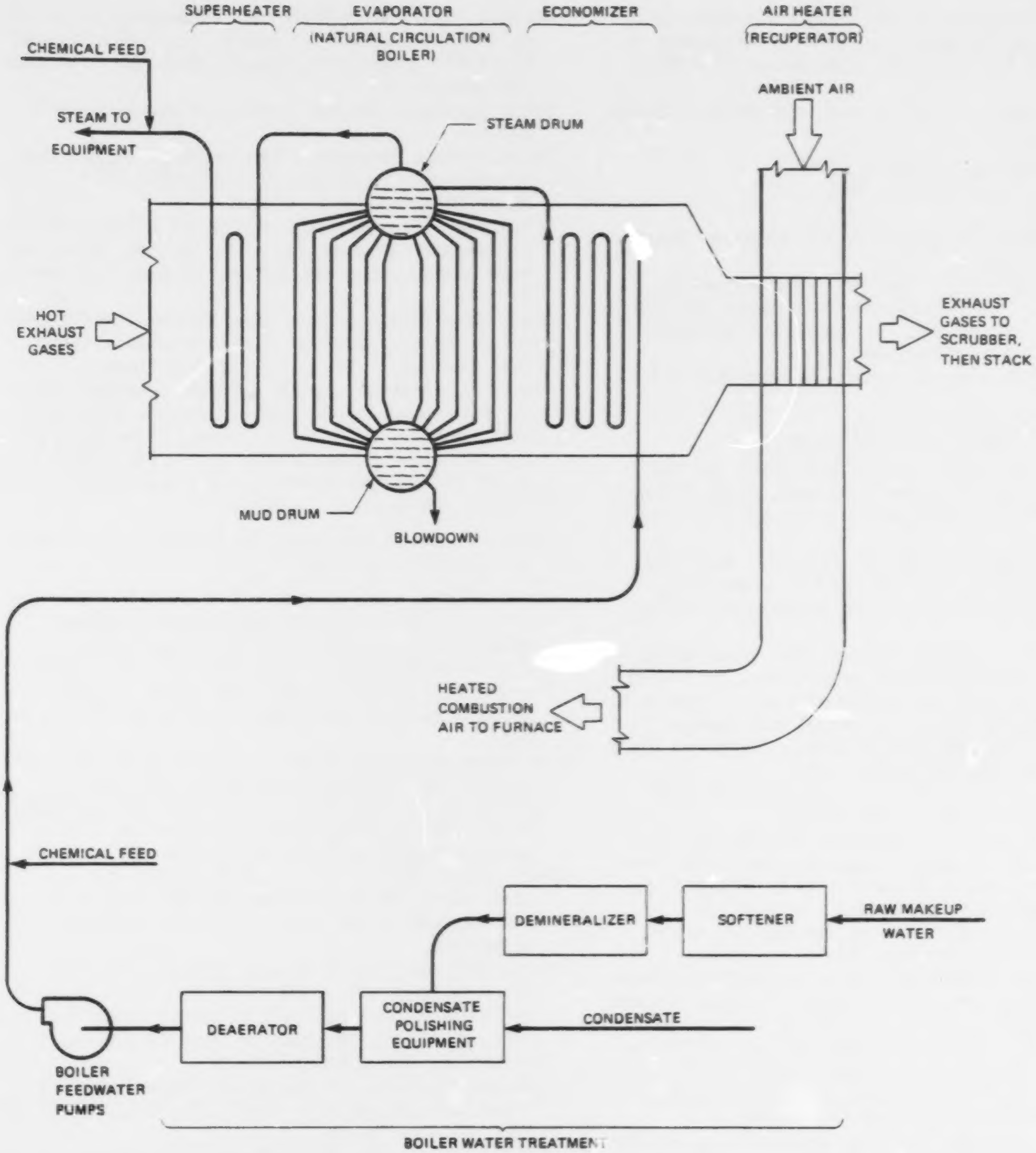

SUPERHEATER
EVAPORATOR
(NATURAL CIRCULATION BOILER)
ECONOMIZER
AIR HEATER
(RECUPERATOR)
CHEMICAL FEED
STEAM TO EQUIPMENT
STEAM DRUM
AMBIENT AIR
HOT EXHAUST GASES
EXHAUST GASES TO SCRUBBER, THEN STACK
MUD DRUM
BLOWDOWN
HEATED COMBUSTION AIR TO FURNACE
CHEMICAL FEED
DEMINERALIZER
SOFTENER
RAW MAKEUP WATER
DEAERATOR
CONDENSATE POLISHING EQUIPMENT
CONDENSATE
BOILER FEEDWATER PUMPS
BOILER WATER TREATMENT

Figure 7–1.—Complex waste heat boiler flowsheet.

additives, etc. Other important concerns of a system include operation and maintenance costs and operator experience and expertise. A small intermittent facility cannot support the capital and operation costs of a complex boiler system, and operators would be difficult to hire. However, a large plant may find that a very efficient heat recovery system saves sufficient fuel and power costs to justify a system as shown on figure 7–1.

Each sludge incineration facility demands a thorough analysis of energy recovery to determine if recovery is practical and, if so, what type of system is most feasible.

Three brief case histories of heat recovery installations are presented below:

Erie, Pa., Wastewater Treatment Plant
Boiler start-up date: August 1974.
Boiler ratings:
design—165 lb/in.^{2} (11.6 kgf/cm^2) saturated steam (700 boiler hp).
actual—15 lb/in.^{2} (1.1 kgf/cm^2) saturated steam.
Furnace data: Two multiple-hearth furnaces, 22 ft, 3 in. (6.78 m) in diameter, 11 hearth, no afterburner, one boiler for each furnace.
Boiler operation: Unfired, continuous operation with furnace.
Backup steam generators: none.
Steam uses: Plant heating and cooling.
Boiler data: Two pass—bare and fin tube; 500 to 700° F inlet, 200° F outlet; evaporator portion only with natural water circulation; three rotating soot blowers.
Treatment: Feedwater—Modul chemicals, deaerator, manual, blowdown (10 sec per hr); condensate, none (95 percent recovery of condensate); steam, none.
O. & M. data: Dedicated engineer and water tender each shift (local ordinance requirement); no forced downtime, systems are alternated every 6 months for furnace repairs; major cost is chemical treatment.

Green Bay Metropolitan Sewage District Treatment Plant
Boiler start-up date: September 1977.
Boiler rating: 100 lb/in.^{2}g (7.03 kgf/cm^2) saturated steam, 36,000 lb/hr (16,330 kg/hr).
Furnace data: Two multiple-hearth furnaces, 22 ft, 3 in. in diameter, 7 hearth, separate afterburner, one waste heat recovery boiler shared by furnaces.
Boiler operation: Unfired, continuous operation.
Backup steam generators: Two package 31 million Btu/hr (9,080,000 W) fired hot water boilers.
Steam uses (in preferential order): Augment plant heating, heat treatment, boiler deaerator heating, preheat for nitric acid solvent, caustic soda tank car heater.
Boiler data: One pass, bare tube; design, 1600° F inlet, 475° F outlet; actual, 1200° F inlet, 400° F outlet; evaporator portion only with natural water circulation no soot blowers or ash removal system.
Treatment: Feedwater, dual bed demineralizer, deaerator, hydrazine, chelates, continuous blowdown; condensate, none (95 percent + recovery of condensate); steam, none.
O. & M. data: No dedicated boiler operator; no downtime since startup; only costs to date are chemicals.

Central Contra Costa Sanitary District Water Reclamation Plant
Boiler start-up date: Expected, June 1978.
Boiler ratings: 170 lb/in.^{2}g (12.0 kgf/cm^2) saturated steam, 35,000 lb/hr (15,880 kg/hr).
Furnace data: Two multiple-hearth furnaces, 22 ft 3 in. (6.78 m) in diameter, 11 hearth, No. 1 hearth used as 1400° F afterburner, 1 waste heat recovery boiler per furnace.
Boiler operation: Unfired, continuous operation with furnace.
Backup steam generators: Two package 23,000 lb/hr (10,430 kg/hr), 170 lb/in.^{2}g (12.0 kgf/cm^2) saturated steam fired water tube boilers.
Steam uses (in preferential order): (1) 2,750 hp (2054 kW) aeration blowers, (2) 81 hp (60 kW) boiler feedwater pumps, plant heating and cooling, CO_2 vaporizers.
Boiler data: One pass-bare tube; design, 1400° F inlet, 450° F outlet; evaporator portion only with natural water circulation; three rotating soot blowers.
Treatment: Feedwater, water softener deaerator, sodium phosphate, sodium sulfite, automatic blowdown by conductivity; condensate, none (95 percent recovery of condensate expected); steam, filming amines.
O. & M. data: Since system not yet operational, actual O & M data are not available.

There are several heat recovery installations in operation or in start-up, such as:

Louisville Metropolitan Sanitation District, Ky.: Three 22 ft 3 in. (6.78 m) diameter × an 8-hearth multiple-hearth furnace, each hearth with 28,000-lb/hr (12,700 kg/hr), 125 lb/in.^{2}g (8.8 kgf/cm^2) saturated steam heat recovery boiler. The steam is used for a sludge heat treatment system and for building heating.
West Berlin, Germany: Three 14 ft 0 in. (4.27 m) diameter fluid-bed furnaces, each with a 3,600-lb/hr (1,630 kg/hr), 360 lb/in.^{2}g (25.3 kgf/cm^2) saturated steam heat recovery boiler. The steam is used for building heating and process equipment.
Tokyo, Japan: Two 11 ft 0 in. (3.35 m) fluid-bed furnaces, each with a 3.4-million Btu/hr (996,000 W) heat recovery boiler. Heat is used for process requirements.
Toronto, Ontario: Two 28 ft 0 in. (8.53 m) fluid-bed furnaces, each with a 26,100-lb/hr (11,800 kg/hr), 260 lb/in.^{2}g (18.3 kgf/cm^2) saturated steam heat recovery boiler. The steam is used for process requirements and building heating.
Leeds Sewage Works, Great Britain: Single-hearth cyclonic furnace with a 12-million Btu/hr (3,516,000 W) heat recovery boiler.
Upper Stour Authority, Great Britain: Single-hearth cyclonic furnace with a 6-million Btu/hr (1,758,000 W) heat recovery boiler.

SLUDGE INCINERATION

Transportation of sewage sludge to its final disposal point demands maximum volume reduction and the highest solids content possible for efficient operation. Treatment methods used to achieve these goals include:

sludge thickening followed by dewatering with vacuum filters, filter presses, or centrifuges; sludge thickening followed by anaerobic digestion and dewatering; chemical stabilization followed by dewatering, etc. Incineration could be used with any of these processes for ultimate volume reduction. The cost of an incineration system has been prohibitive at many locations because of inexpensive, readily available disposal alternatives, such as sludge lagoons, ocean disposal or land disposal with short-haul distances. Increasing restrictions on the disposal of sewage sludge and decreasing availability of suitable land have increased the importance of sludge volume reduction to the point where incineration is now a viable consideration in many wastewater treatment plants. Public health concerns regarding polychlorinated biphenoles (PCBs) and pathogenic bacteria, both of which are destroyed during combustion, also increases the use of incineration.

Although the heat value of sludge is fairly high (5,000 to 10,000 Btu/lb dry solids) (11,600 J/g to 23,200 J/g), the water content of most sludges requires the addition of auxiliary fuel to maintain combustion in the furnace. Fuel cost is a major operational cost of incineration. The reduction of this cost can be achieved by raising the solids content of the sludge, thereby increasing the net heat value, or by lowering the amount of inert material in the sludge prior to incineration.

Many processes which reduce the moisture content of the sludge increase the amount of inert material in the sludge. Anaerobic digestion decreases the volatile content and increases the inert content of the sludge. This results in a lower sludge heat value but produces a digester gas which is commonly used in the treatment plant. Sludge from physical-chemical treatment processes has a high content of inert material but tends to dewater better than sludge from biological processes. Autogenous or self-sustained combustion is possible with some sludge feeds but is dependent on the net heat content of the sludge. When incineration is considered as the final sludge processing step, the benefits and penalties of the conditioning steps on the fuel consumption of the furnace must be evaluated. These pretreatment steps include the addition of lime, ferric salts, or ash to the sludge to improve the operation of the dewatering equipment. These materials reduce the heat content of the sludge and, thus, represent an increase in the amount of inert material which has to be heated during incineration.

Sludge incineration can be considered to occur in four steps:

1. Temperature of the sludge is raised to 212°F.
2. Water is evaporated from the sludge.
3. Water vapor temperature and air temperature are increased.
4. Temperature of the sludge is raised to the ignition point of the volatiles.

The heat evolved by the incineration of sludge can be utilized in many ways: heating and drying of the incoming sludge, production of steam for space heating, powering mechanical equipment, or generating electricity. Because of the relatively high temperature of the combustion gases, approximately 1300 to 1700°F, and the excess air injected into the furnace, a large amount of the heat evolved is used to raise the temperature of the incoming mixture of combustion air and fuel.

For successful incineration, proper mixing of the combustion gases, the fuel mixture and the volatile solids in the sludge are important. There are two types of furnaces generally used for sludge incineration in the United States—the multiple-hearth and the fluid-bed. The single-rotary hearth cyclonic furnace has several installations in Great Britain, Europe, and Japan and is also available in the United States. The electric furnace is a relatively new development, but there are a number of installations in the United States at small sewage treatment plants. All four furnaces provide adequate mixing of sludge with the combustion gases and a residence time which insures complete combustion. There are other types of furnaces available for sludge incineration, but they are not discussed herein.

Three hypothetical plants have been used to compare the different furnaces; the general design criteria are given in table 7–1. The solids content of the sludge as fed to the incinerator is assumed to be either 20 or 40 percent, depending upon the alternative. A general flow sheet of the hypothetical plants is given on figure 7–2. When these data are further developed in later tables, it should be noted that the volatile solids for the 40 percent solids cake has been reduced in most cases

Table 7–1.—Hypothetical wastewater treatment plant design data

Alternate	IA	IB	IIA	IIB	IIIA	IIIB
Flow, Mgal/d	5	5	15	15	50	50
Total solids, lb/day dry basis	10,320	10,320	31,000	31,000	103,000	103,000
Volatile solids, percent of dry solids	77	77	77	77	77	77
Furnace operation, hr/week	40	40	80	80	168	168
Furnace loading rate, lb/hr dry basis	1,810	1,810	2,710	2,710	4,300	4,300
Solids content of furnace feed, percent solids by weight	20	40	20	40	20	40
Furnace loading rate, lb/hr wet basis	9,030	4,515	13,560	6,780	21,460	10,730

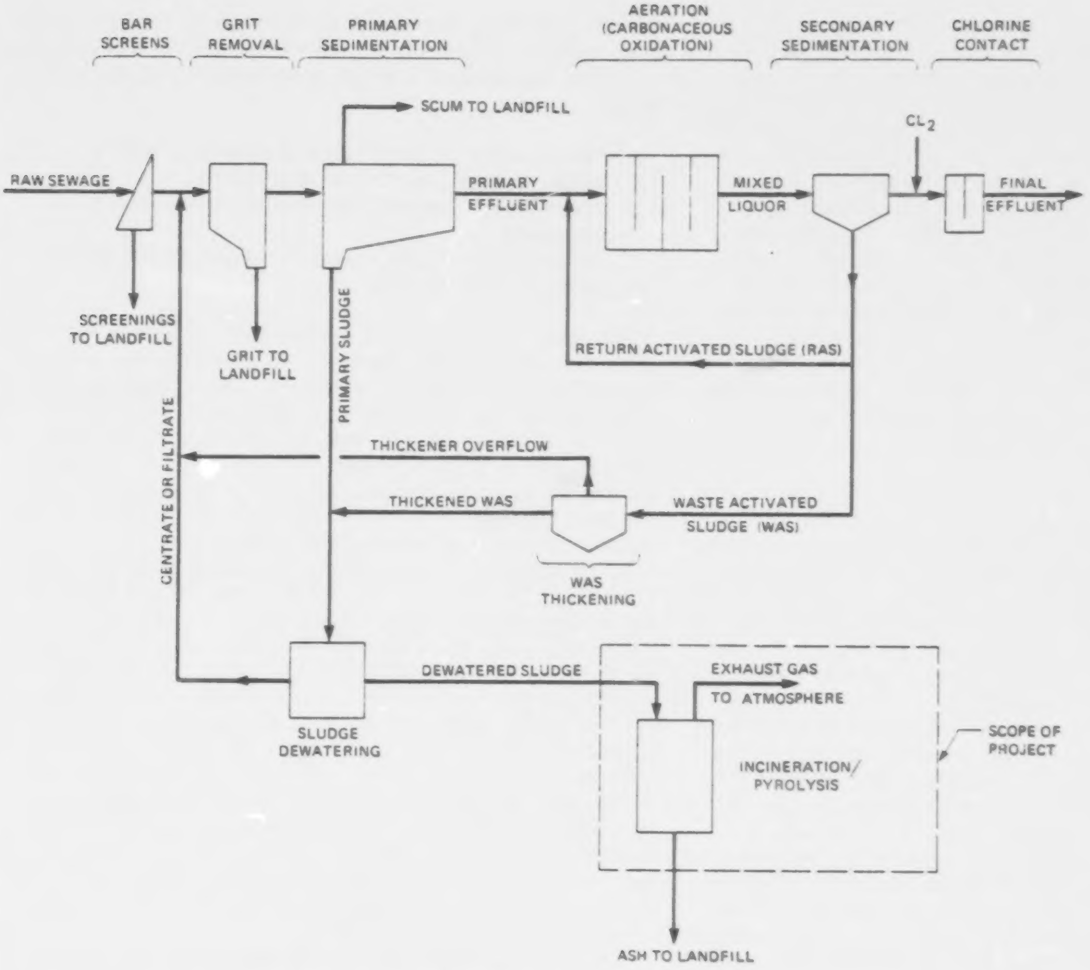

BAR SCREENS
GRIT REMOVAL
PRIMARY SEDIMENTATION
AERATION (CARBONACEOUS OXIDATION)
SECONDARY SEDIMENTATION
CHLORINE CONTACT
SCUM TO LANDFILL
CL2
RAW SEWAGE
PRIMARY EFFLUENT
MIXED LIQUOR
FINAL EFFLUENT
SCREENINGS TO LANDFILL
GRIT TO LANDFILL
PRIMARY SLUDGE
RETURN ACTIVATED SLUDGE (RAS)
CENTRATE OR FILTRATE
THICKENER OVERFLOW
THICKENED WAS
WASTE ACTIVATED SLUDGE (WAS)
WAS THICKENING
DEWATERED SLUDGE
EXHAUST GAS TO ATMOSPHERE
SCOPE OF PROJECT
INCINERATION/ PYROLYSIS
SLUDGE DEWATERING
ASH TO LANDFILL

Figure 7–2.—Hypothetical wastewater treatment plant flowsheet.

to 65 percent to allow for lime or ferric chloride addition as a filter aid.

The heat and mass balance tables indicate the amount of fuel and power a sludge furnace requires for the different treatment plants considered in this paper. Operational costs can be estimated based on the requirements for supplemental fuel and connected horsepower. General sizes and types of support facilities such as ash handling equipment, water supply for the air pollution equipment and fuel requirements can also be estimated based on the data shown in the tables. It should be noted that no start-up fuel demands are shown for the multiple-hearth furnace. The difference in the amount of fuel and connected horsepower for the furnaces when burning sludge with 20 percent solids and sludge with 40 percent solids indicates that an economic evaluation of the solids dewatering system is warranted when evaluating sludge combustion.

Multiple-Hearth Furnace

The multiple-hearth furnace (MHF) is the most widely used sludge incinerator in the United States. The furnace is durable, relatively simple to operate, and can successfuly handle wide fluctuations in feed quality and loading rate. The MHF is a vertically oriented, cylindrically shaped, refractory-lined, steel shell containing a series of horizontal refractory hearths, one above the other. Multiple-hearth furnaces are available with diameters ranging from 4 ft 6 in. (1.37 m) to 29 ft (8.84 m) with four to fourteen hearths. A typical section of a MHF is shown on figure 7–3. A central shaft runs the height of the furnace and supports rabble arms above each hearth. There are either two or four rabble arms per hearth. Each arm contains several rabble teeth or plows which rake the sludge spirally across the hearth as the arm rotates above each hearth. In figure 7–3,

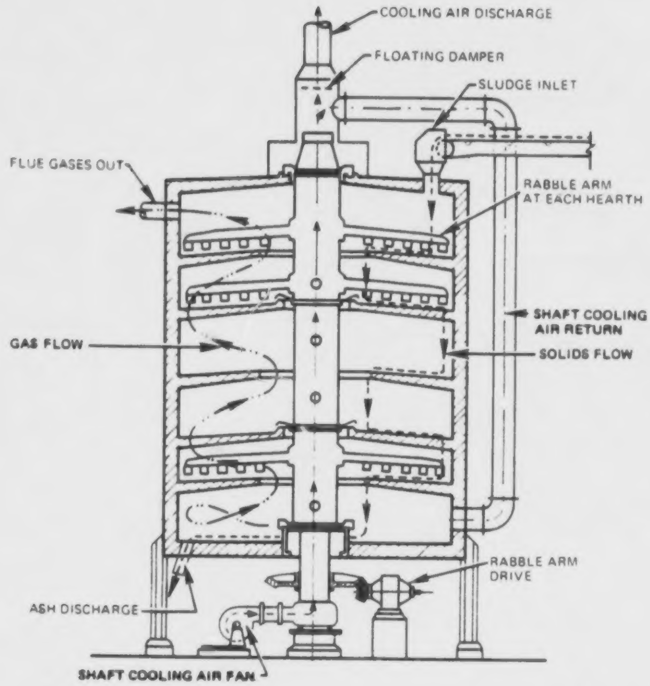


Figure 7–3.—Cross section of a multiple hearth furnace.

sludge is fed at the periphery of the top hearth and is raked toward the center where it drops to the hearth below. On the second hearth, the sludge is raked outward to holes at the periphery of the bed where the sludge drops to the next hearth. The alternating drop hole locations on each hearth and the counter-current flow or rising exhaust gases and descending sludge provide good contact between the hot combustion gases and the sludge feed to insure complete combustion.

The central shaft is normally of cast iron and has an inner tube called the cold air tube. Each of the rabble arms is connected to the cold air tube and has a return tube which returns the heated cooling air to the annular space between the cold air tube and the shell of the central shaft which serves as an exhaust passageway for the cooling air. Cooling air is fed to the cold air tube by the cooling air fan. The heated cooling air is usually taken from the top of the central shaft and reinjected into the lowest hearth as preheated combustion air. Cooling air vented to the atmosphere represents a heat loss of roughly the same magnitude as radiation.

The MHF can be divided into four zones during incineration. The first zone, which consists of the upper hearths, is the drying zone where most of the water is evaporated; the second zone, generally consisting of the central hearths, is the combustion zone, where temperatures reach 1400 to 1700°F; the third zone is the fixed carbon burning zone, which oxidizes the carbon to carbon dioxide; and the fourth zone is the cooling zone, which includes the lowest hearths. In this zone, the ash is cooled by rejecting heat to the incoming combustion air. The sequence of these zones is always the same, but the number of hearths in each zone is dependent on the quality of the feed, the design of the furnace, and the operational conditions.

When the thermal quality of the sludge feed is insufficient to sustain autogenous combustion, burners supply the additional heat by operating either continuously or intermittently on all or selected hearths. Generally, off-gas temperatures of 600°F, or lower, indicate incomplete combustion and a need for supplemental fuel. Off-gas temperatures from 800 to 1600°F indicate complete combustion. When autogenous, the off-gas temperatures are usually maintained below 1400°F by eliminating preheating of the combustion air and by adding excess air. Excess air requirements for the MHF are generally 75 to 100 percent of stoichiometric requirements when sludge is the furnace feed material. Excess air is also used for ash cooling.

A flow sheet for the MHF is given on figure 7–4. Energy and mass balances for the MHF for the treatment plant alternatives are given in tables 7–2 and 7–3 for use with figure 7–4.

Multiple-hearth furnace manufacturers use different loading rates based upon varied experience in incineration. This variation results in a range of recommended furnace sizes, although the cost range is not significant. These costs, however, do not represent a bid condition.

For areas where air pollution requirements are similar to those for the San Francisco Bay Area, the MHF would require an afterburner, fired with supplemental fuel. This requirement would increase fuel consumption, equipment size, and capital and operating costs from those shown in tables 7–2 and 7–3.

The MHF can operate successfully over a large range of operating modes and feeds. Operating problems have included failure of rabble arms and teeth and failure of hearth refractories. The problems with the rabble arm and teeth have generally been solved by using different construction materials. The refractory problem is usually caused by improper operation and is a disadvantage which must be considered when evaluating an MHF. An MHF generally requires at least 24 hours to cool off to ambient temperature or be brought back to operating temperature from ambient temperature. During intermittent operation, supplemental fuel is usually fired to maintain the temperature of the furnace during the hours when it is not being used so that the long heating time for the furnace can be reduced. When the furnace is heated or cooled too quickly, the refractories can be damaged. Multiple-hearth furnaces should not be operated at temperatures above 1800°F; thus, with high-energy fuels, there may be operational problems due to high temperature in the combustion zone.

Fluid-Bed Furnace

The fluid-bed furnace (FBF) is a vertically oriented, cylindrically shaped, refractory-lined, steel shell which

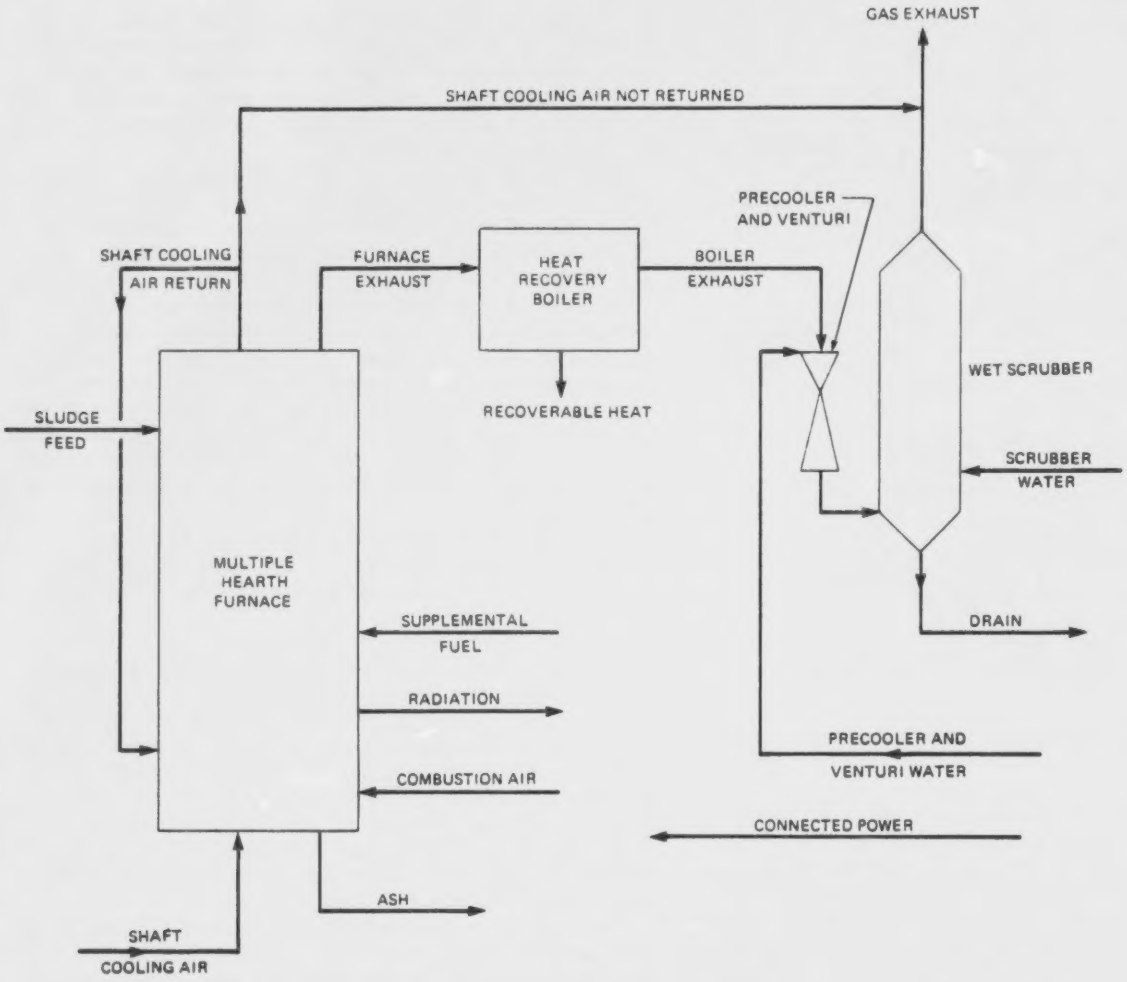

GAS EXHAUST
SHAFT COOLING AIR NOT RETURNED
PRECOOLER AND VENTURI
SHAFT COOLING AIR RETURN
FURNACE EXHAUST
HEAT RECOVERY BOILER
BOILER EXHAUST
WET SCRUBBER
RECOVERABLE HEAT
SLUDGE FEED
SCRUBBER WATER
MULTIPLE HEARTH FURNACE
SUPPLEMENTAL FUEL
DRAIN
RADIATION
PRECOOLER AND VENTURI WATER
COMBUSTION AIR
CONNECTED POWER
ASH
SHAFT COOLING AIR

Figure 7–4.—Flowsheet for sludge incineration in a multiple-hearth furnace.

contains the bed and fluidizing air diffusers. The FBF is normally available in sizes from 9 ft (2.74 m) to 25 ft (7.62 m) in diameter. However, there is one industrial unit operating with a diameter of 53 ft (16.15 m). A cross section of the fluid-bed furnace is shown on figure 7–5. The sand bed is approximately 2.5 ft (0.76 m) thick and sits on a refractory-lined grid. This grid contains truyeres through which air is injected into the bed at a pressure of 3 to 5 lb/in.^{2}g (0.21 to 0.35 kgf/cm^2) to fluidize the bed. Bed expansion is approximately 80 to 100 percent. Temperature of the bed is controlled between 1400 and 1500°F by auxiliary burners located either above or below the sand bed and in some installations by a water spray or heat removal system above the bed which reduces the furnace temperature when it is too high. Ash is carried out the top of the furnace and is removed by air pollution control devices, usually wet venturi scrubbers. Sand, which is carried out with the ash, must be replaced. Sand loss is approximately 5 percent of the bed volume every 300 hrs of operation. Furnace feed is introduced either above or directly into the bed, depending on the type of feed. Generally, sewage sludge is fed directly into the bed.

Excess air requirements for the FBF vary from 20 to 40 percent. This reduces supplemental fuel requirements and reduces heat losses from heating and exhausting excess air as compared to a multiple-hearth furnace. The mixing action caused by the air flowing through the bed and the injection of sludge directly into the bed ensures complete contact between the sludge solids and the combustion gases.

There are two basic configurations for the FBF. In the

Table 7–2.—Material and heat balance for sludge incineration in a multiple-hearth furnace; manufacturer A[a]

Stream	Alternate					
	IA 5 Mgal/d 20 percent solids	IB 5 Mgal/d 40 percent solids	IIA 15 Mgal/d 20 percent solids	IIB 15 Mgal/d 40 percent solids	IIIA 50 Mgal/d 20 percent solids	IIIB 50 Mgal/d 40 percent solids
Furnace design						
Diameter (ft–in.)	18–9	14–3	22–3	16–9	22–3	18–9
Number of hearths	7	6	7	6	10	7
Hearth loading rate (lb wet solids/sq ft/hr)	7.3	9.3	7.4	9.5	8.4	10.3
Sludge feed						
lb dry solids/hr	1,806	2,133	2,713	3,200	4,293	5,064
Heat value (MM Btu/hr)	13.91	13.93	20.89	20.90	33.06	33.07
Volatile content (percent dry solids)	77	65	77	65	77	65
Supplemental fuel						
No. 2 fuel oil (lb/hr)	143	—	205	—	312	—
Heat value (MM Btu/hr)	2.64	—	3.79	—	5.77	—
Combustion air						
Volume at 60° F (lb/hr)	22,060	27,531	32,959	41,544	51,945	66,740
Shaft cooling air						
Volume (lb/hr)	19,273	9,178	24,321	13,766	34,416	19,273
Shaft cooling air return						
Volume at 325° F (lb/hr)	16,560	—	20,880	—	29,520	—
Heat value (MM Btu/hr)	1.26	—	1.59	—	2.25	—
Shaft cooling air not recovered						
Heat loss (MM Btu/hr)	0.22	0.71	0.28	1.06	0.40	1.48
Ash						
Volume at 500° F (lb/hr)	415	740	624	1,110	987	1,757
Heat value (MM Btu/hr)	0.04	0.07	0.06	0.10	0.09	0.15
Radiation						
Heat loss (MM Btu/hr)	0.32	0.21	0.41	0.26	0.53	0.33
Furnace exhaust						
Volume (lb/hr)	[b]30,817	[c]32,123	[b]46,102	[c]48,434	[b]72,735	[c]77,643
Heat value (MM Btu/hr)	15.96	12.94	23.93	19.48	37.81	31.11
Boiler exhaust						
Heat value at 500° F (MM Btu/hr)	13.26	9.64	19.73	12.28	31.11	19.61
Recoverable heat						
100 percent efficiency (MM Btu/hr)	2.70	3.30	4.20	7.20	6.70	11.50
Precooler and Venturi water feed						
Flow at 70° F (gal/min)	90	86	135	130	215	209
Scrubber water feed						
Flow at 70° F (gal/min)	182	174	273	260	429	418
Scrubber drain						
Flow (gal/min)	296	264	428	398	676	638
Temperature (F)	98	98	98	98	98	98
Gas exhaust						
Volume (lb/hr)	26,667	38,938	44,278	58,646	61,116	91,393
Temperature (F)	142	170	139	168	138	166
Heat value (MM Btu/hr)	9.44	6.00	14.01	6.80	22.09	10.82
Connected power						
Horsepower	238	93	305	178	305	238
Installed cost (MM dollars)	2.0	1.6	2.2	2.0	2.4	2.0

[a] All data supplied by the manufacturer.
[b] At 800° F.
[c] At 1,000° F.

Table 7–3.—Material and heat balance for sludge incineration in a multiple-hearth furnace; manufacturer B[a]

Stream	Alternate					
	IA 5 Mgal/d 20 percent solids	IB 5 Mgal/d 40 percent solids	IIA 15 Mgal/d 20 percent solids	IIB 15 Mgal/d 40 percent solids	IIIA 50 Mgal/d 20 percent solids	IIIB 50 Mgal/d 40 percent solids
Furnace design						
Diameter (ft–in.)	22–3	16–9	22–3	18–9	22–3	18–9
Number of hearths	5	5	7	5	10	7
Hearth loading rate (lb wet solids/sq ft/hr)	6.9	6.4	7.4	7.6	8.4	8.7
Sludge feed						
lb dry solids/hr	1,806	1,806	2,712	2,712	4,292	4,292
Heat value (MM Btu/hr)	13.91	13.91	20.88	20.88	33.05	33.05
Volatile content (percent dry solids)	77	77	77	77	77	77
Supplemental fuel						
No. 2 fuel oil (lb/hr)	119	—	175	—	271	—
Heat value (MM Btu/hr)	2.32	—	3.39	—	5.23	—
Combustion air						
Volume at 70° F (lb/hr)	21,400	20,688	32,050	32,039	50,592	51,273
Shaft cooling air						
Volume (lb/hr)	11,970	10,710	17,100	11,970	23,940	17,100
Shaft cooling air return						
Volume at 350° F (lb/hr)	11,970	—	17,000	—	23,940	—
Heat value (MM Btu/hr)	0.75	—	1.07	—	1.50	—
Shaft cooling air not returned						
Heat loss (MM Btu/hr)	—	0.67	—	0.75	—	1.07
Ash						
Volume at 600° F (lb/hr)	415	415	623	623	987	987
Heat value (MM Btu/hr)	0.05	0.05	0.08	0.08	0.13	0.13
Radiation						
Heat loss (MM Btu/hr)	0.29	0.20	0.36	0.23	0.47	0.30
Furnace exhaust						
Volume (lb/hr)	[b]30,134	[c]24,788	[b]45,162	[c]38,196	[b]71,336	[c]61,017
Heat value (MM Btu/hr)	15.89	12.99	23.83	19.82	37.68	31.55
Boiler exhaust						
Heat value at 500° F (MM Btu/hr)	12.99	7.00	19.49	10.63	30.82	16.89
Recoverable heat						
100 percent efficiency (MM Btu/hr)	2.90	5.99	4.34	9.19	6.86	14.66
Precooler and Venturi water feed						
Flow at 70° F (gal/min)	117	92	167	133	253	203
Scrubber water feed						
Flow at 70° F (gal/min)	228	228	342	205	540	327
Scrubber drain						
Flow (gal/min)	350	331	530	346	828	540
Temperature (F)	132	116	133	116	134	116
Gas exhaust						
Volume (lb/hr)	23,015	22,285	34,473	46,466	54,418	72,297
Temperature (F)	110	169	110	156	110	155
Heat value (MM Btu/hr)	1.82	2.43	2.72	3.48	4.29	5.44
Connected power						
Horsepower	250	150	250	200	350	200
Installed cost (MM dollars)	1.6	1.2	1.8	1.4	2.0	1.5

[a] All data supplied by the manufacturer.

[b] At 800° F.

[c] At 1,000° F.

first system, the fluidizing air passes through a heat exchanger or recuperator prior to injection into the combustion chamber. This arrangement is known as a hot windbox. In the second system, the fluidizing air is injected directly into the furnace and is known as a cold windbox. The first arrangement increases the thermal efficiency of the system by utilizing the high temperature of the exhaust gases to heat the incoming combustion air.

A general flow sheet for the FBF is given on figure 7–6. Energy and material balances for the fluid-bed furnace for the treatment plant alternatives are given in table 7–4 for use with figure 7–6.

The FBF has a slightly lower capital cost than the MHF. Start-up fuel requirements are low, and no fuel is required for start-up following an overnight shutdown. The fluid-bed furnace has a minimum of mechanical components and is relatively simple to operate. The sand bed acts as a large heat reservoir which minimizes the amount of fuel required to reheat the system following shutdown. This makes the FBF very attractive for intermittent operation. Since normal operation of the FBF results in exhaust temperatures in excess of 1400°F, there is no requirement for an afterburner using supplemental fuel to comply with air emissions regulations in some areas as may be required with the MHF.

The main problems with the FBF have been with the feed system and temperature control with high-energy feeds. Screw feeds and pump feeds have jammed be-

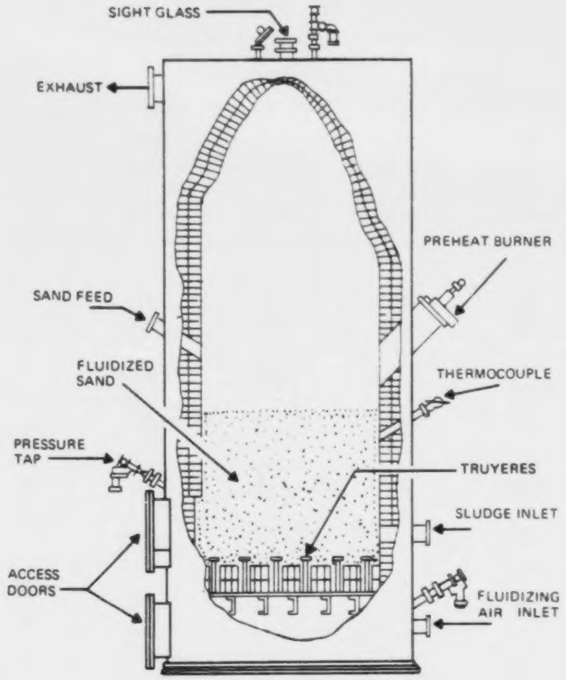

SIGHT GLASS
EXHAUST
PREHEAT BURNER
SAND FEED
FLUIDIZED SAND
THERMOCOUPLE
PRESSURE TAP
TRUYERES
SLUDGE INLET
ACCESS DOORS
FLUIDIZING AIR INLET

Figure 7–5.—Cross section of a fluidized bed furnace.

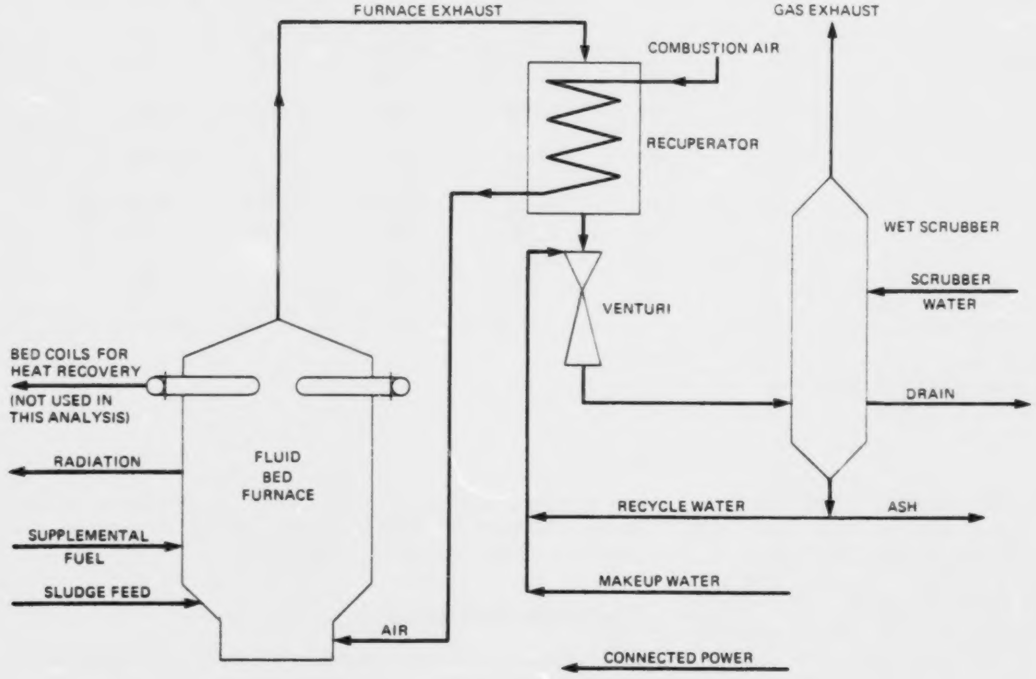

FURNACE EXHAUST
GAS EXHAUST
COMBUSTION AIR
RECUPERATOR
WET SCRUBBER
SCRUBBER WATER
VENTURI
BED COILS FOR HEAT RECOVERY (NOT USED IN THIS ANALYSIS)
DRAIN
FLUID BED FURNACE
RADIATION
RECYCLE WATER
ASH
SUPPLEMENTAL FUEL
SLUDGE FEED
MAKEUP WATER
AIR
CONNECTED POWER

Figure 7–6.—Flowsheet for sludge incineration in a fluid bed furnace.

Table 7–4.—Material and heat balance for sludge incineration in a fluid bed furnace; Dorr-Oliver, Inc.[a]

Stream	Alternate					
	IA 5 Mgal/d 20 percent solids	IB 5 Mgal/d 40 percent solids	IIA 15 Mgal/d 20 percent solids	IIB 15 Mgal/d 40 percent solids	IIIA 50 Mgal/d 20 percent solids	IIIB 50 Mgal/d 40 percent solids
Furnace design						
Inside diameter (ft)	14	12	18	14	22	18
Loading rate (lb wet solids/sq ft/hr)	56.9	47.0	53.3	47.0	56.5	45.0
Sludge feed						
lb dry solids/hr	1,810	2,132	2,710	3,192	4,300	5,065
Heat value (MM Btu/hr)	13.93	13.93	20.87	20.87	33.10	33.10
Volatile solids (percent dry solids)	77	65	77	65	77	65
Supplemental fuel[b]						
Volume (lb/hr)	151	—	224	—	353	—
Heat value (MM Btu/hr)	2.80	—	4.14	—	6.52	—
Combustion air						
Volume (lb/hr)	19,353	16,250	28,976	23,576	45,978	38,620
Heat value (MM Btu/hr)	4.4	—	6.7	—	10.6	—
Ash						
Volume (lb dry solids/hr)	416	746	623	1,117	959	1,772
Heat value (MM Btu/hr)	0.12	0.14	0.18	0.26	0.29	0.42
Water flow (gal/min)	20	32	30	43	40	70
Radiation						
Heat loss (MM Btu/hr)	0.42	0.29	0.63	0.44	1.00	0.71
Recoverable heat						
100 percent efficiency (MM Btu/hr)	[c]5.0	[d]8.9	[c]7.5	[d]13.4	[c]12.0	[d]18.1
Recuperator	Yes	No	Yes	No	Yes	No
Venturi water						
Recycle water (gal/min)	83	68	124	102	197	161
Makeup water at 70° F (gal/min)	10	12	15	19	24	30
Scrubber water feed						
Flow at 70° F (gal/min)	365	345	548	565	868	824
Scrubber drain						
Flow at 130° F (gal/min)	391	359	582	600	924	900
Gas exhaust						
Volume (ACFM)	5,042	3,972	7,524	5,949	12,007	9,459
Temperature (F)	120	120	120	120	120	120
Connected power						
Horsepower	218	162	320	234	425	350
Installed cost (MM dollars)	1.1	1.0	1.4	1.1	1.6	1.5

[a] All data provided by Dorr-Oliver, Inc.

[b] Afterburner not necessary to meet SFBAAPCD regulations.

[c] At 1,400° F.

[d] At 1,650° F.

cause of overdrying the sludge when it is injected directly into the bed. When spray nozzles have been used, thermocouples have occasionally burned out. These problems have generally been solved by using different materials. There have been some problems with preheaters and with scaling of the sand on the venturi scrubber. In some installations, there have been serious erosion problems in the scrubber due to the excessive carryover of bed material and the resulting sandblasting effect. The fluid-bed incinerator can be operated at 2200° F and is suitable for high energy sludges when appropriately designed. Since there is a minimum of air always required for bed fluidizing, energy savings in turndown (feed reduction) are minor.

Cyclonic Furnace

The cyclonic furnace, sometimes called a single-rotary hearth furnace, is a vertically oriented, cylindrically shaped, refractory-lined, steel shell normally with a domed cover. There is one rotating hearth and a fixed plow which moves the combustible material from the

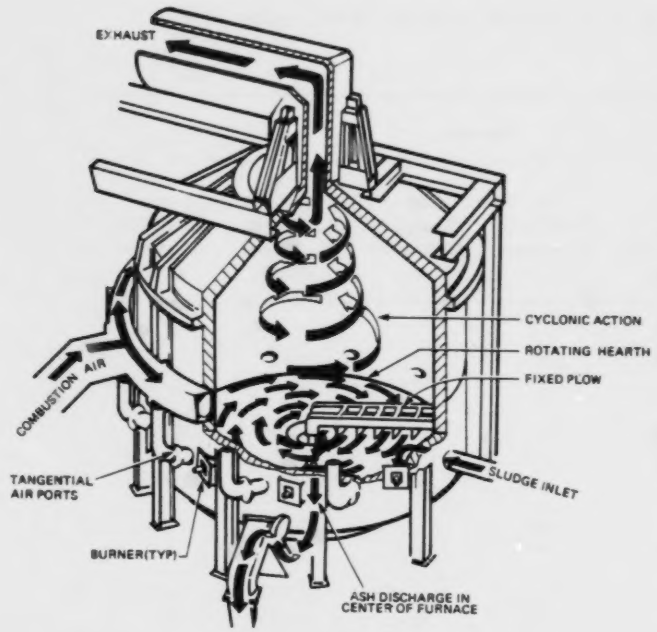

EXHAUST
CYCLONIC ACTION
ROTATING HEARTH
FIXED PLOW
COMBUSTION AIR
TANGENTIAL AIR PORTS
SLUDGE INLET
BURNER(TYP)
ASH DISCHARGE IN CENTER OF FURNACE

Figure 7-7.—Cross section of a cyclonic furnace.

outer edge of the hearth to the center. The furnaces are available with hearths to 30 ft (9.14 m) in diameter but larger sizes can be built. The sludge is fed by a screw feeder which deposits the sludge near the periphery of the rotating hearth. A sectional view of the furnace is given on figure 7-7.

This furnace design differs from the multiple-hearth and fluid-bed designs in that it does not allow the combustion air to pass upward through the feed material. Combustion air and auxiliary fuel, if required, are injected tangentially into the combustion chamber above the rotating hearth, creating a swirling action which mixes the gases and allows adequate contact between the oxygen and the furnace feed. The gases from the combustion process spiral upward to the outlet. The furnace exhaust temperature is approximately 1500°F and can be used for heat recovery, preheat of inlet air, or wasted. The ash is circulated to the middle of the hearth, where it drops through the hearth to a quench tank for final disposal. The rotating hearth is sealed at the edges by a water bath.

A general flow sheet for the furnace is given on figure 7-8. Energy and material balances for the cyclonic furnace are given in table 7-5 for use with figure 7-8.

The low capital cost of this furnace and the low fuel requirements make it a competitive alternative furnace

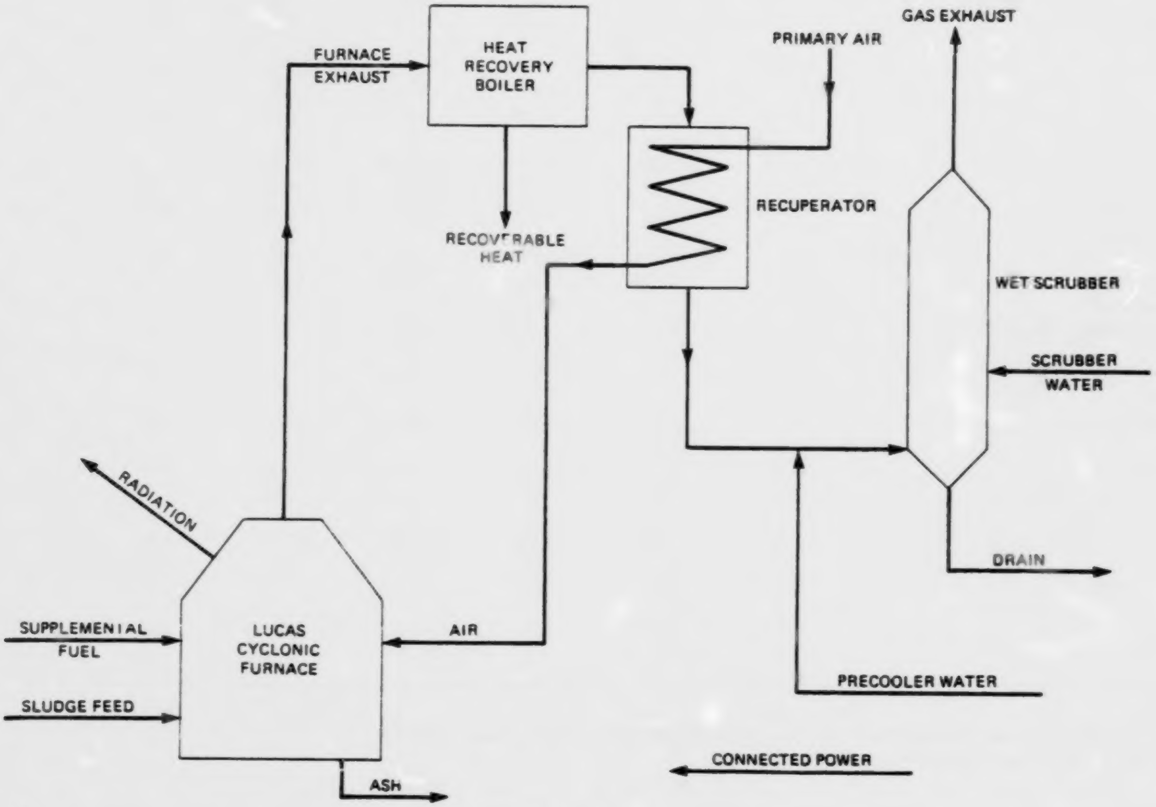

FURNACE EXHAUST
HEAT RECOVERY BOILER
RECOVERABLE HEAT
PRIMARY AIR
RECUPERATOR
GAS EXHAUST
WET SCRUBBER
SCRUBBER WATER
RADIATION
DRAIN
SUPPLEMENTAL FUEL
SLUDGE FEED
LUCAS CYCLONIC FURNACE
AIR
PRECOOLER WATER
ASH
CONNECTED POWER

Figure 7-8.—Flowsheet for sludge incineration in a cyclone furnace.

Table 7–5.—Material and heat balance for sludge incineration in a cyclonic furnace; AFB Engineers and Contractors, Inc.[a]

Stream	Alternate					
	IA 5 Mgal/d 20 percent solids	IB 5 Mgal/d 40 percent solids	IIA 15 Mgal/d 20 percent solids	IIB 15 Mgal/d 40 percent solids	IIIA 50 Magl/d 20 percent solids	IIIB 50 Mgal/d 40 percent solids
Furnace design						
Diameter (ft–in)	19–6	13–9	24–0	17–0	30–3	21–6
Hearth loading rate (lb wet solids/sq ft/hr)	30.4	30.9	30.1	30.1	29.9	29.7
Sludge feed						
lb dry solids/hr	1,806	1,806	2,712	2,712	4,292	4,292
Heat value (MM Btu/hr)	14.27	14.27	21.43	21.43	33.91	33.91
Volatile solids (percent dry solids)	77	77	77	77	77	77
Supplemental fuel[b]						
Volume (lb/hr)	132	—	184	—	546	—
Heat value (MM Btu/hr)	2.48	—	3.46	—	10.28	—
Primary air						
Volume (lb/hr)	19,665	19,665	29,519	29,519	46,694	46,694
Temperature (F)	1,100	60	1,100	60	1,100	60
Burner air						
Volume at 60° F (lb/hr)	2,280	—	3,178	—	9,430	—
Ash						
Volume at 260° F (lb/hr)	415	415	624	624	987	987
Heat value (MM Btu/hr)	0.19	0.19	0.29	0.29	0.46	0.46
Radiation						
Heat loss (MM Btu/hr)	0.90	0.60	1.17	0.80	2.0	1.00
Waste heat boiler	No	Yes	No	Yes	No	Yes
Recuperator	Yes	No	Yes	No	Yes	No
Furnace exhaust						
Volume (lb/hr)	30,692	23,765	45,817	35,675	77,143	57,424
Temperature (F)	1,420	1,411	1,420	1,421	1,420	1,420
Heat value (MM Btu/hr)	19.90	13.48	29.75	20.34	50.10	32.38
Boiler/recuperator exhaust						
Temperature (F)	960	500	960	500	960	500
Heat value (MM Btu/hr)	15.66	6.87	23.43	10.32	39.45	16.51
Recoverable heat—boiler						
100 percent efficiency (MM Btu/hr)	—	6.61	—	10.02	—	15.87
Precooler water feed						
Flow at 60° F (gal/min)	12	5	19	7	30	15
Scrubber water feed						
Flow at 60° F (gal/min)	292	197	437	296	699	507
Scrubber drain						
Flow (gal/min)	319	207	477	311	763	535
Temperature (F)	120	110	120	110	120	110
Gas exhaust						
Volume (lb/hr)	23,468	21,209	34,969	31,838	62,225	49,002
Temperature (F)	120	110	120	110	120	110
Heat value (MM Btu/hr)	1.79	1.62	2.67	2.43	4.75	3.74
Connected power						
Horsepower	175	125	260	190	460	290
Installed cost (MM dollars)	1.3	1.0	1.6	1.1	[c]N/A	1.5

[a] All data provided by AFB Engineers/Contractors sole U.S. distributors of the Lucas Cyclonic Furnace.

[b] Afterburners not necessary to meet SFBAAPCD regulations.

[c] Not available.

for sludge incineration. However, there are presently no units operating on a sludge feed in the United States. A pilot unit was run for approximately 2 years at the San Leandro, Calif., wastewater treatment plant, but the unit has been dismantled.

The rotary-hearth furnace has a relatively low capital cost and is mechanically simple with only one rotating hearth; however, the feed system is very similar to the feed system of the fluid-bed furnace, which has had problems as previously described. Because of the high exhaust temperatures, no afterburner or supplemental heater would be required with the cyclonic furnace to comply with air emissions regulations in the San Francisco Bay Area. Additional heat could be recovered in a waste heat boiler with the exhaust gas from the recuperator because of the temperature of this gas.

Electric Furnace

The electric, or infrared, furnace (EF) is a horizontally oriented, rectangular, ceramic fiber blanket-lined, steel shell containing a moving horizontal woven-wire belt and electric radiant heating elements. Electric furnaces are available in a range of sizes from 4 ft (1.22 m) wide by 20 ft (6.1 m) long to 9.5 ft (2.9 m) wide by 96 ft (29.26 m) long; larger sizes are currently under development. A typical cross section is shown on figure 7–9. Sludge is fed into the furnace through a feed hopper which drops the sludge onto the conveyer belt. The sludge is leveled by means of an internal roller to a layer approximately 1 in. (2.54 cm) thick, spanning the width of the belt. This layer of sludge moves under the heating elements, which provide supplementary energy, if required, to effect the incineration process. Ash is discharged from the end of the belt to the ash handling system. Combustion air flow is countercurrent to the sludge flow, with most of the combustion air being introduced into the ash discharge end of the unit. There is normally no rabbling or plowing of the sludge as it is conveyed through the furnace.

The EF can be divided into three general zones: the feed zone, the drying and combustion zone, and the ash discharge zone. The feed and discharge zone are each 8 ft (2.44 m) long. The length of the drying and combustion zone varies with each design. A flow sheet for the electric furnace is shown on figure 7–10. Energy and mass balances for the treatment plant alternatives are given in table 7–6 for use with figure 7–10. In addition to the alternative cases I, II, and III, similar information for a 1-mgd treatment plant application has been included as the EF is suited to relatively small wastewater treatment plants.

The hearth loading rate of the EF, in the larger sizes, is slightly greater than that of a multiple-hearth furnace. The supplemental energy (or fuel) requirements of the EF is much less than the requirements of the MHF, FBF, or the cyclonic furnace. This is due to the low excess combustion air requirements of 20 percent and the absence of cooling or fluidizing air requirements. However, the energy source is electric rather than the fossil fuel used by the other systems, and since electricity is generally a more expensive energy source, the advantage is reduced somewhat, depending upon the cost differential of the alternate fuels.

The capital cost combined with a relatively low energy demand make this an attractive furnace, especially for small treatment systems. By using ceramic fiber blanket insulation, instead of solid refractories, the electric furnace may be shut down and heated up without refractory problems, which can occur in the other furnaces previously discussed. This makes the EF suitable for intermittent operation. However, each restart requires auxiliary energy since there is no heat sink such as the sand bed in the FBF. There are presently no units installed with a capacity over 1,200 pounds per hour. The first electric furnace was put into operation in Richardson, Tex., in 1975, so there are only 2 years of performance data available.

The electric furnace appears to be a feasible alterna-

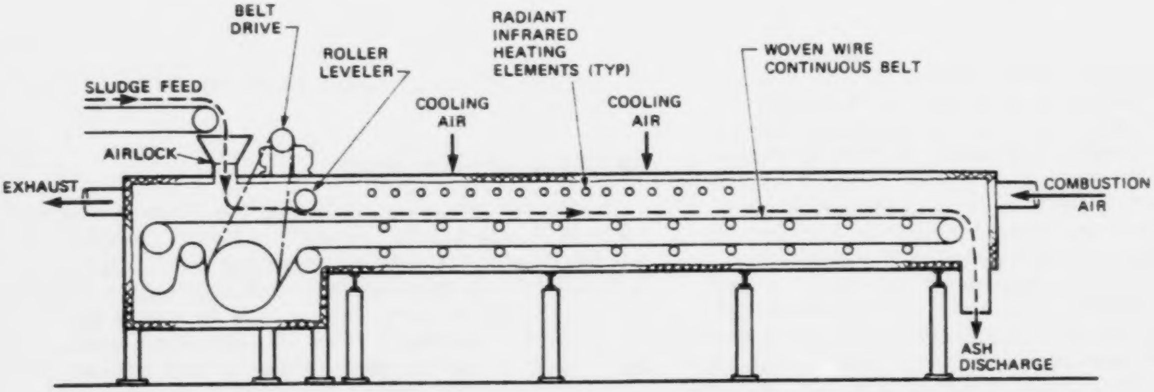
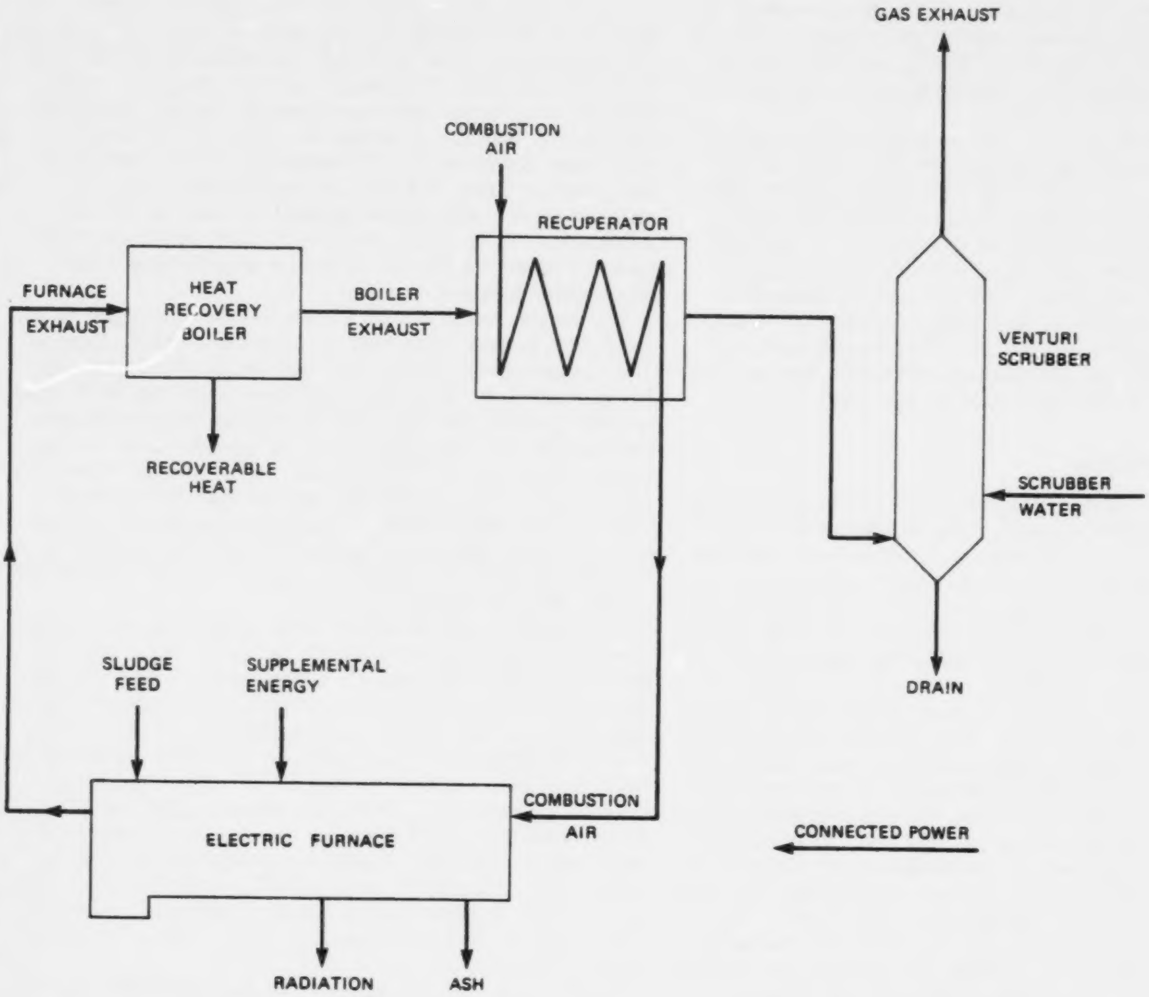


Figure 7–9.—Cross section of an electric furnace.



GAS EXHAUST
COMBUSTION AIR
RECUPERATOR
FURNACE EXHAUST
HEAT RECOVERY BOILER
BOILER EXHAUST
VENTURI SCRUBBER
RECOVERABLE HEAT
SCRUBBER WATER
SLUDGE FEED
SUPPLEMENTAL ENERGY
DRAIN
COMBUSTION AIR
ELECTRIC FURNACE
CONNECTED POWER
RADIATION
ASH

Figure 7–10.—Flowsheet for sludge incineration in an electric furnace.

tive for both small and large systems due to inherent simplicity, cost and energy demand, but this furnace requires considerably more floor space than other furnaces which are vertically oriented. Connected horsepower, whether for heating or motive power, may create a significant electric utility demand charge in some areas, regardless if the energy is used or not. Due to the gas flow being countercurrent to the sludge flow, the electric furnace may require an afterburner to comply with the prohibitory regulations of the SFBAAPCD. This requirement would increase the supplemental energy requirement, the amount of equipment, and capital and operating costs from those shown in table 7–6. Air emission control equipment would tend to be smaller to allow for the low excess air requirements than other furnaces of similar feed capacity.

SLUDGE PYROLYSIS

Due to the rising fuel costs and the inherent heating value of sludge fed to incinerators, partial pyrolysis, or more correctly, starved-air combustion (SAC), has been investigated and demonstrated in multiple-hearth furnaces to be a means of combusting sludge without large amounts of supplementary fuel. Based upon current data, SAC of sludges with a solids content of over 25 percent is possible without the addition of fossil fuel while maintaining an afterburner temperature over

Table 7–6.—Material and heat balance for sludge incineration in an electric infrared furnace; Shirco, Inc.[a]

Stream	Alternate						
	IA 5 Mgal/d 20 percent solids	IB 5 Mgal/d 40 percent solids	IIA 15 Mgal/d 20 percent solids	IIB 15 Mgal/d 40 percent solids	IIIA 50 Mgal/d 20 percent solids	IIIB 50 Mgal/d 40 percent solids	1 Mgal/d 40 percent solids
Furnace design							
Number of units	2	1	2	1	3	2	1
Overall width (ft)	8.5	8.5	9.5	9.5	9.5	8.5	6
Overall length (ft)	72	72	88	88	96	88	32
Belt area per furnace (sq ft)	382.6	382.6	560.5	560.5	616.8	479.5	94.5
Loading rate (lb wet solids/sq ft/hr)[b]	11.8	13.9	12.1	14.3	11.6	13.2	11.3
Sludge feed							
lb dry solids/hr	1,806	2,133	2,713	3,200	4,293	5,064	427
Heat value (MM Btu/hr)	13.91	13.91	20.89	20.89	33.06	33.06	2.79
Volatile content (percent dry solids)	77	65	77	65	77	65	65
Water (lb/hr)	7,224	3,200	10,582	4,800	17,172	7,596	641
Heat value (MM Btu/hr)	0.28	0.12	0.41	0.18	0.65	0.29	0.02
Supplemental power							
Electric infrared (kW)	280.8	—	402.5	—	643.8	—	—
Heat value (MM Btu/hr)	[c]0.96	—	[c]1.37	—	[c]1.88	—	—
Combustion air							
Volume at 60°F (lb/hr)	17,736	24,786	26,676	37,184	42,161	58,844	4,962
Heat value (MM Btu/hr)	0.26	0.36	0.38	0.54	0.61	0.85	0.07
Ash							
Volume at 500°F (lb/hr)	415	747	624	1,120	987	1,772	149
Heat value (MM Btu/hr)	0.10	0.18	0.16	0.28	0.24	0.44	0.04
Radiation							
Heat loss (MM Btu/hr)	0.36	0.18	0.47	0.24	0.77	0.43	0.07
Furnace exhaust							
Volume (lb/hr)	[d]26,351	[e]29,372	[d]39,616	[e]44,064	[d]62,628	[e]69,732	[e]5,880
Heat value (MM Btu/hr)	14.95	14.03	22.42	21.09	34.54	33.34	2.70
Boiler exhaust							
Heat value at 500°F (MM Btu/hr)	13.00	8.53	19.49	12.79	31.33	20.23	1.71
Recoverable heat							
100 percent efficiency (MM Btu/hr)	1.95	5.50	2.93	8.30	3.21	13.11	0.99
Scrubber water feed							
Flow at 70°F (gal/min)	397	201	584	314	1,049	498	201
Scrubber drain							
Flow (gal/min)	390	196	606	306	1,081	485	196
Temperature (F)	120	120	120	120	120	120	150
Gas exhaust							
Volume (lb/hr)	29,538	35,811	39,616	53,838	54,744	85,186	7,183
Temperature (F)	120	120	120	120	120	120	120
Heat value (MM Btu/hr)	1.98	2.77	2.96	4.18	4.71	6.57	0.55
Total connected power							
Horsepower	[f]22	25	[f]30	40	[f]50	60	7
Total installed cost (MM dollars)	1.0	0.7	1.3	0.9	1.5	1.2	0.3

[a] All data supplied by Shirco, Inc.

[b] Useable area of belt.

[c] Autogenous with combustion air preheated to 500°F.

[d] At 750°F.

[e] At 1,200°F.

[f] Does not include supplemental power requirements for infrared heaters.

1400°F; however, nominal solids level for autogenous SAC is a function of the net heating value of the sludge. Starved-air combustion reduces sludge to an ash containing up to 30 percent combustibles and up to 20 percent fixed carbon, depending upon the method of operation of the MHF. The gas produced from the destruction of sludge has a heat value of up to 90 Btu/-standard dry cubic foot (sdcf) and is suitable for many applications. Starved-air combustion is more thermally efficient than incineration because of the small amount of air, 25 to 50 percent of the theoretical air required for combustion, that must be heated to combustion temperature. This prevents wasting energy to heat excess air in the furnace and reduces the size and, hence, the capital cost of the gas-handling facilities. Fluid-bed, cyclonic, and electric furnaces could also be operated as SAC reactors although to date, none of these furnaces have been operated in this manner with a pure sludge feed. An FBF has been used to make charcoal, a SAC operation, and research is underway to pyrolyze wood waste with the FBF.

Development and Application

Autogenous pyrolysis (SAC) of sludge was successfully demonstrated in a full-size project with an MHF at a wastewater treatment plant at Concord, Calif., near San Francisco, operated by The Central Contra Costa Sanitary District. The project was funded by the Environmental Protection Agency, the State of California, and the Central Contra Costa Sanitary District. Sludge from the plant had a heating value of 9,000 Btu/lb (20,900 J/s) volatile solids, a volatile solids content of 75 percent, and was centrifuged to a solids content of 24 percent. The SAC reactor was a converted six-hearth, 18-ft, 9-in. (5.71 m) diameter MHF. The centrifuged sludge was pyrolyzed without any auxiliary fuel, either in the furnace or the afterburner, while maintaining an afterburner temperature of 1400°F. The fuel gas had a heating value of 90 Btu/sdcf. Other significant results of this two-month test program included:

- Pyrolysis was found to be easier to control than incineration.
- Hearth temperature was used to control the furnace, using air addition as the manipulated variable.
- In SAC, air addition to the furnace should be automatically controlled.
- Particulate production on a solids-fed basis was about 50 percent lower using SAC than incineration.
- Although the controlled variable in SAC was temperature, the degree of pyrolysis, as measured by the amount of feed heating value remaining uncombusted in the fuel gas, is actually controlled by the fraction of the theoretical air required for combustion that is added to the reactor.
- During the corrosion tests, the most resistant alloys for SAC were type HK stainless steel and Inconel 690 for high temperature conditions and Hastelloy C-276 and Inconel 625 for low temperature conditions.

Additional details of the test work and application for the Central Contra Costa Sanitary Dictrict can be found in references 3, 9, 10, 11, 38, and 44.

Two furnace manufacturers, BSP Division of Envirotech Corp., and Nichols Engineering & Research Corp., a subsidiary of Neptune International, are actively involved in ongoing research and development of SAC systems. Because of this research, there are refinements and updating of design parameters regularly; therefore, the data presented here are approximate only. A typical flow sheet for a MHF operated as a SAC reactor is shown on figure 7–11. Energy and material balances for the SAC systems are shown in table 7–7 for the wastewater alternatives previously described.

Advantages and Disadvantages

With all of the test work, much of which is still underway, SAC in a MHF was found to have many significant advantages as compared to incineration or other combustion process. These advantages include:

- Easier and more positive control of the combustion process.
- More stable operation with little response to changes in feed.
- Greater solids feed capacity due to higher hearth loading rates.
- All equipment used is currently being manufactured and has a long performance history.
- Reduced particulates and other air emissions.
- Significant reduction in fuel usage including afterburning at 1400°F.
- Autogenous SAC can occur at lower sludge solids content than incineration.
- Slightly lower operating costs.
- Most existing MHFs can easily be retrofitted to operate in a SAC mode.

These advantages are clearly shown in table 7–8 where MHF for incineration and SAC are compared.

As expected, with many advantages there are significant disadvantages, such as:

- Need for afterburner may limit use in existing installations with space problems.
- More instrumentation is required.
- Must be very careful of bypass stack exhaust since furnace exhaust is high in hydrocarbons and may be combustible in air. This may result in bypassing only after afterburning with appropriate emergency controls.
- Corrosivity of furnace exhaust gases.
- Combustibles in ash may create ultimate disposal problems.

Although there are several disadvantages, it is apparent that they are outweighted by the advantages, particularly in this era of high energy costs. With sound engineering

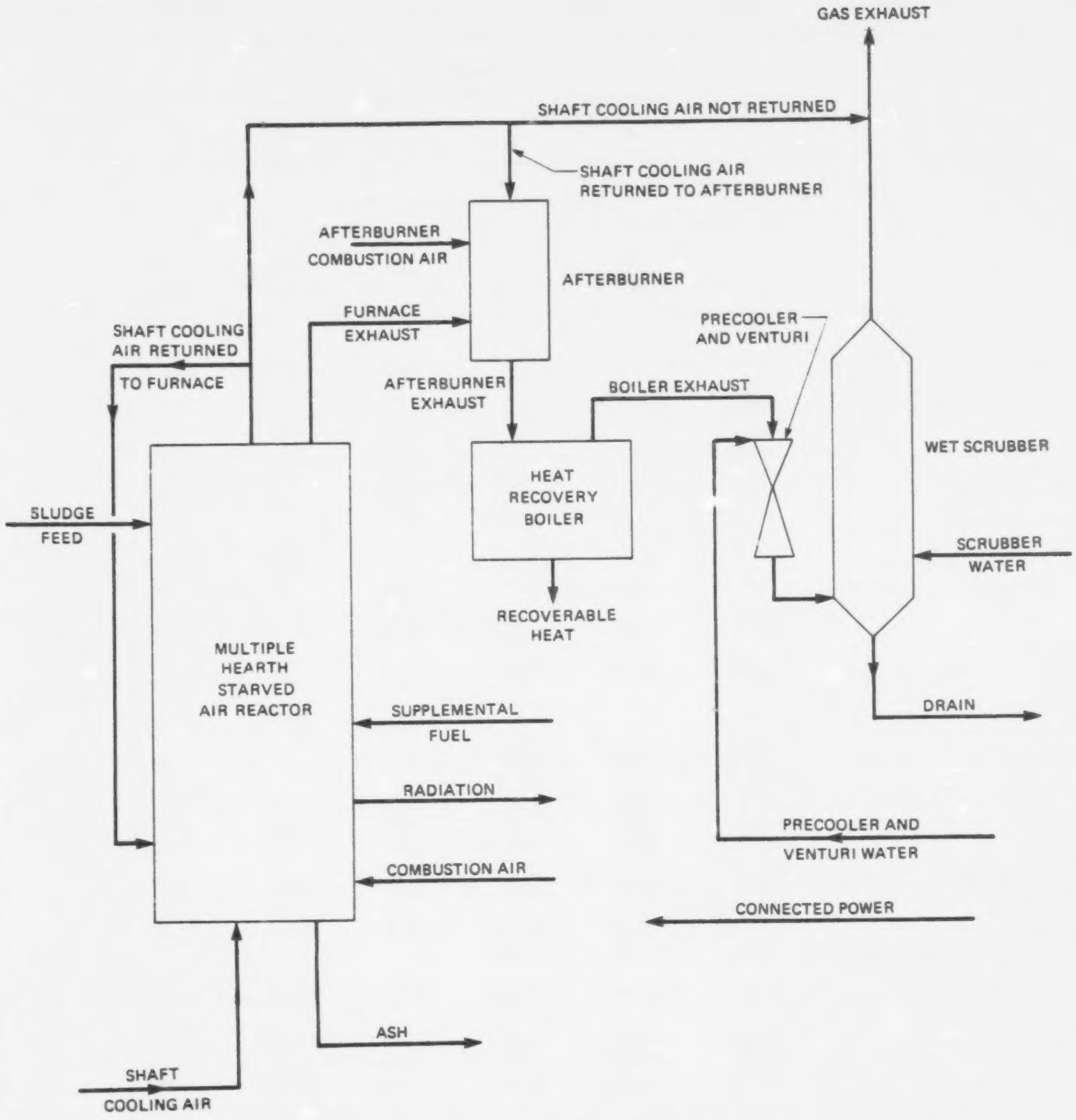

GAS EXHAUST
SHAFT COOLING AIR NOT RETURNED
SHAFT COOLING AIR RETURNED TO AFTERBURNER
AFTERBURNER COMBUSTION AIR
AFTERBURNER
FURNACE EXHAUST
SHAFT COOLING AIR RETURNED TO FURNACE
PRECOOLER AND VENTURI
AFTERBURNER EXHAUST
BOILER EXHAUST
WET SCRUBBER
HEAT RECOVERY BOILER
SLUDGE FEED
SCRUBBER WATER
RECOVERABLE HEAT
MULTIPLE HEARTH STARVED AIR REACTOR
SUPPLEMENTAL FUEL
DRAIN
RADIATION
PRECOOLER AND VENTURI WATER
COMBUSTION AIR
CONNECTED POWER
ASH
SHAFT COOLING AIR

Figure 7–11.—Flowsheet for starved-air combustion of sludge in a multiple-hearth furnace.

practices and a thorough system analysis, all of the disadvantages can be resolved.

Conversion of Existing Systems

One of the significant advantages of SAC is that most existing MHF systems can be converted to operate as SAC reactors. This retrofitting involves relatively few changes, and the costs and benefits are site specific. One definite incentive for conversion is that the existing system may be able to handle projected waste loads without the addition of more incinerators. This incentive is demonstrated in a design example presented later in this paper. Assuming an increase in solids loading of

Table 7–7.—Material and heat balance for starved-air combustion of sludge in a multiple-hearth furnace[a]

Stream	Manufacturer					
	A			B		
	Alternate (all 40 percent solids feed)					
	IB 5 Mgal/d	IIB 15 Mgal/d	IIIB 50 Mgal/d	IB 5 Mgal/d	IIB 15 Mgal/d	IIIB 15 Mgal/d
Furnace design						
Diameter (ft–in.)	12–9	14–3	16–9	16–9	18–9	22–3
Number of hearths	6	7	8	5	5	5
Hearth loading rate (lb wet solids/sq ft/hr)	12.1	12.0	11.4	7.6	9.0	9.6
Sludge feed						
lb dry solids/hr	2,132	3,200	5,064	2,132	3,200	5,064
Heat value (MM Btu/hr)	7.35	10.73	16.90	13.91	20.88	33.05
Volatile solids (percent dry solids)	65	65	65	65	65	65
Supplemental fuel	—	—	—	—	—	—
Combustion air						
Volume (lb/hr)	—	[b]780	[b]1,500	13,210	19,473	32,107
Temperature (F)	—	60	60	70	70	70
Shaft cooling air						
Volume (lb/hr)	9,178	10,095	15,602	10,710	12,206	12,206
Shaft cooling air return						
Volume at 350° F (lb/hr)	6,480	8,640	13,380	—	—	—
Shaft cooling air to stack						
Volume at 325° F (lb/hr)	—	—	—	10,710	12,206	12,206
Shaft cooling air to afterburner						
Volume at 350° F (lb/hr)	2,698	1,455	2,222	—	—	—
Ash						
Volume (lb/hr)	787	1,181	1,869	740	1,112	1,760
Temperature (F)	500	500	500	900	900	900
Heat value (MM Btu/hr)	0.23	0.34	0.54	0.10	0.14	0.23
Radiation						
Heat loss (MM Btu/hr)	0.44	0.62	0.94	0.14	0.15	0.21
Furnace exhaust						
Volume at 800° F (lb/hr)	11,010	16,250	25,658	[c]N/A	[c]N/A	[c]N/A
Heat value (MM Btu/hr)	6.82	10.16	16.05			
Afterburner combustion air						
Volume at 60° F (lb/hr)	[d]4,382	[d]8,805	[d]14,098	[c]N/A	[c]N/A	[c]N/A
Afterburner exhaust						
Volume (lb/hr)	17,638	26,537	42,041	17,799	26,360	43,008
Temperature (F)	1,495	1,495	1,495	1,600	1,600	1,600
Heat value (MM Btu/hr)	12.76	19.18	30.04	13.91	19.75	31.78
Boiler exhaust						
Heat value at 500° F (MM Btu/hr)	6.76	9.18	13.04	6.62	9.89	15.80
Recoverable heat						
100 percent efficiency (MM Btu/hr)	6.0	10.0	17.0	7.29	9.86	15.98
Precooler and Venturi water feed						
Flow at 70° F (gal/min)	51	77	121	72	102	155
Scrubber water feed						
Flow at 70° F (gal/min)	102	153	243	123	183	293
Scrubber drain						
Flow (gal/min)	160	240	380	203	295	465
Temperature (F)	98	98	98	120	125	126

See footnotes at end of table.

Table 7–7.—Material and heat balance for starved-air combustion of sludge in a multiple-hearth furnace—Continued

Stream	Manufacturer					
	A			B		
	Alternate (all 40 percent solids feed)					
	IB 5 Mgal/d	IIB 15 Mgal/d	IIIB 50 Mgal/d	IB 5 Mgal/d	IIB 15 Mgal/d	IIIB 15 Mgal/d
Gas exhaust						
Volume (lb/hr)	14,280	21,480	34,080	25,063	33,137	46,837
Temperature (F)	120	120	120	160	173	155
Heat value (MM Btu/hr)	4.62	5.96	7.94	1.79	2.40	3.47
Connected power						
Horsepower	78	123	218	100	150	200
Installed cost (MM dollars)	1.4	1.6	2.3	1.3	1.5	1.8

[a] All data supplied by the manufacturers.

[b] In addition to shaft cooling air returned to furnace.

[c] Not available.

[d] In addition to shaft cooling air returned to afterburner.

Table 7–8.—Comparison of multiple-hearth furnaces used for incineration and starved-air combustion of sludge[a]

	Furnace size (ft–in. × hearths)	Hearth loading rate (lb wet solids/sq ft/hr)	Maximum heat recovery (MM Btu/hr)	Installed cost (MM dollars)
Alternate IB				
Manufacturer A				
Incineration	14–3 × 6	9.3	3.30	1.6
SAC	12–9 × 6	12.1	6.00	1.4
Manufacturer B				
Incineration	16–9 × 5	6.4	5.99	1.2
SAC	16–9 × 5	7.6	7.29	1.3
Alternate IIB				
Manufacturer A				
Incineration	16–9 × 6	9.5	7.20	2.0
SAC	14–3 × 7	12.0	10.00	1.6
Manufacturer B				
Incineration	18–9 × 5	7.6	9.19	1.4
SAC	18–9 × 5	9.0	9.86	1.5
Alternate IIIB				
Manufacturer A				
Incineration	18–9 × 7	10.3	11.50	2.0
SAC	16–9 × 8	11.4	17.00	2.3
Manufacturer B				
Incineration	18–9 × 7	8.7	14.66	1.5
SAC	22–3 × 5	9.6	15.98	1.8

[a] Data extracted from tables 7–2, 7–3, and 7–7.

approximately 30 percent, the basic changes necessary are:

Change	*Reason*
Addition of an afterburner (if existing system has an afterburner, size may have to be increased. If furnace is large enough, top hearth may be used as an afterburner; however, refractories must be examined).	Required to burn combustible fuel gas prior to exhaust.
Addition of combustion air flow control and temperature controllers.	Required to control SAC process.
Possible replacement of combustion air fan.	May be required to provide necessary pressure for proper control of air to furnace and to reduce air flow rate.
Modification of induced draft fan—may be only speed change or damper position.	Required since total system, including afterburner, uses less than 50 percent excess air.
Review and modify venturi and wet scrubber.	Required to maintain high performance with lower air flows. Also may need precooler section if boiler is not in process train.
Add additional emission control equipment.	Required, depending upon local air emission control regulations regarding applicability of new source performance standards. Converted SAC system will reduce emissions as compared to present incinerator.
Review furnace system and replacement of remote instrumentation.	Good practice for any major process revision.
General "tightening up" of furnace system.	SAC process depends upon good air control; therefore, peak and poke holes must be modified along with several other penetrations into the furnace.

With these modifications and others deemed necessary during the review of the system, the retrofitted SAC system is suitable for operation.

COCOMBUSTION OF SLUDGE AND OTHER MATERIALS

Wastewater treatment plant sludges have a high water content which results in a fairly low net heat value. Sludges produced by advanced wastewater treatment processes contain a lower percentage of volatile solids than less sophisticated treatment processes which also results in a fairly low net heating value. The heat content of volatile solids in sewage sludge is approximately 10,000 Btu/lb (23,200 J/s). Depending upon the percent of volatile solids in the sludge and the heat content of the volatile solids, autogenous incineration of wastewater treatment sludges is only possible with a sludge solids content of 30 to 35 percent or greater. Since gravity or flotation thickening can only produce a sludge of about 5 to 10 percent solids, some type of dewatering process must be used to raise the sludge solids content or auxiliary fuel will be required for combustion. With fossil fuel costs increasing rapidly and availability being curtailed, any combustion system that requires a constant feed of power, either fossil fuel or electricity, will in most cases be uneconomical. If sludge is combined with other combustible materials, in a cocombustion scheme, a furnace feed can be created that has both a low water content and a heat value high enough to sustain autogenous combustion.

There are a variety of materials that can be combined with sewage sludge to create a furnace feed with a higher heat value than sludge. Some materials are: municipal solid waste, coal, wood wastes (sawdust), textile wastes, bagasse, and farm wastes, such as corn stalks, rice husks, etc. Virtually any material that can be burned can be combined with sludge. An advantage of cocombustion is that many times a waste material, municipal or industrial, can be disposed while providing an autogenous sludge feed thereby effecting a solution to two disposal problems.

In recent studies, the addition of pulverized coal to liquid sludge showed that coal addition improves filtration efficiency and results in a much higher solids content and heat value in the filter cake than if the coal is added directly to the sludge cake. Addition of the coal to the sludge results in a furnace feed that has a higher solids content and heat value than sludge alone. This reduces or eliminates the demand for supplemental fuel. This approach is a solution to the problem of maintaining a high volatile solids content with a low moisture content; however, coal is not a refuse material, and the utilization of coal to improve filtration and increase the fuel value of the furnace feed is a substitution of one fossil fuel for another, not a replacement of fossil fuel with a material of little current value. On the other hand, coal is considered to be an available fuel as compared with other fossil fuels, and this approach could be appropriate in some parts of the country.

Two plants, Rochester, N.Y., and Vancouver, Wash., are experimenting with sawdust as a filter aid prior to combustion. The results to date have been very good but detailed data are not yet available.

There are currently many sludge and solid waste cocombustion systems, including incineration and pyrolysis, that are being operated, tested, or demonstrated in full-scale plants. Codisposal technology is continually being revised and updated because of this ongoing work. However, the systems described herein have been operated at full-scale, have been thoroughly reviewed and, although not necessarily fully developed, have sufficient background to be implemented wherever the particular system proves cost-effective.

Coincineration Methods (Sludge and Municipal Refuse)

Coincineration of sewage sludge with raw municipal refuse has historically not been successful in conventional solid waste incinerators. Incomplete combustion of the sludge indicated that failures were due to inadequate contact of the sludge and refuse, high sludge water content and inadequate detention time in the furnace. Generally, it appeared that existing solid waste incinerators were not easily adaptable to sludge incineration, and that mixing of the sludge and refuse prior to incineration was not feasible because of the variation in size, density and composition of the materials commonly found in municipal wastes; however, several systems are currently in operation which have been specifically designed to incinerate solid waste with sewage sludge, and these are described herein.

Fluid Bed

Municipal solid waste and sewage sludge have been coincinerated in a fluid-bed furnace in Franklin, Ohio, since 1971, which began as an EPA-supported resource recovery demonstration project. A wet pulper removes ferrous metal and heavy solids from 150 tons (136 Mg) per day of shredded refuse. Fiber is recovered from the pulper effluent by selective screening and elutriation, and all unrecovered residuals are conveyed to a barrel thickener. Sludge from a 2.5-Mgal/d secondary treatment plant is added to the thickened residuals, and the combined stream is dewatered in a cone press to solids content of 45 percent before injection into the furnace. The furnace feed is blown into the bed about 1 ft over the truyeres. There is a buildup in bed volume with this coincineration scheme, and a small amount of bed material must be removed periodically from the furnace. The preparation steps reduce the amount of noncombustible material in the furnace feed to between 3 and 6 percent. Feed size is 1/2 in. (1.27 cm) or less. A detailed review of this system is presented in reference 2.

In a normal dry shredding and separation operation, the feed stock would not be as uniform as it is at Franklin, Ohio. If the feed to the fluid-bed furnace is not uniform in both size and density, material will tend to sift downward through the bed. This material must be removed quickly or it could upset the air flow through the bed. Systems are in operation which can continuously remove settled noncombustible material from the bed.

Waterwall Combustion

Three waterwall combustion units in Europe are presently incinerating solid waste and sewage sludge. At Dieppe, France, 54 tons (49 Mg) of solid waste and 21 tons (19 Mg) of dried sludge are incinerated daily. Digested sludge with a solids content of 4 percent is pumped from the wastewater treatment plant and dried with 350°F process steam in two thin film evaporators to a solids content of 55 percent. The vapors generated are returned to the furnace. The dried sludge is conveyed to the charging chutes of the furnace and is mixed with the solid waste from the receiving pit. A small plant at Brive, France, is similar to Dieppe except raw sludge is used rather than digested sludge.

A waterwall combustion unit at the Krefeld plant near Dusseldorf, Germany, processes 600 tons (544 Mg) of solid waste and 45 tons (41 Mg) of dried sewage solids daily. The facility generates electricity for the wastewater treatment plant, the incineration facility, and exports hot water for use in the community. Raw sludge with a solids content of 5 percent is pumped from the wastewater treatment plant to the disposal facility. The sludge is centrifuged to a solids content of 25 percent and then flash-dried with 1500°F flue gases in a vertical shaft flash drying chamber. The powdered sludge is then suspension-fired by injection into the furnace immediately above the top of the flame. The facility has been in operation for 2 years.

Incineration With Flue Gas Drying

Two plants in the United States use the flue gases generated in a solid waste refractory lined incinerator to dry the sewage sludge prior to combustion with solid waste. In Ansonia, Connecticut, sludge with 4 percent solids is dried in a disk type cocurrent spray dryer with 1200°F incinerator flue gases. Dried sludge and vapors are injected into the incinerator for suspension burning. The plant capacity is 200 tons (181 Mg) per day of solid waste. Presently the sludge is not being incinerated but is being used as a soil conditioner. Holyoke, Mass., utilizes a similar incinerator and averages 50 tons (45 Mg) per day throughput; however, the sludge is dewatered to 28 percent solids prior to drying in a rotary drier using hot flue gases. Dried sludge and vapors are also suspension fired.

Incineration With Furnace Drying

Recently at Norwalk, Conn., a process was tested in which a stoker-fired incinerator was used to coincinerate sludge and solid waste. In this project the sludge cake, with a solids content of 5 percent, was sprayed onto the front wall of the charging chute to form a thin sludge layer on top of the refuse. The sludge layer dries and burns during the 30 minutes residence time in the incinerator. This process has been incorporated into the design of a plant at Glen Cove, N.Y., which will burn a mixture of 12.5 percent sludge (at 20 percent solids) and 87.5 percent refuse. The plant is designed to produce 2.2 megawatts of power, sufficient to meet the demands of the sewage treatment plant and the incineration facility. The Glen Cove facility is currently in construction and should be completed in three years.

Multiple-Hearth

Several plants in England and Europe have been practicing coincineration in multiple-hearth furnaces for several years; however, serious problems such as severe erosion of the hearths, poor temperature control, refractory failures, and air pollution have accompanied these projects. All of these problems appear to be a direct result of poor preprocessing of solid waste prior to addition into the furnace. Poor preprocessing causes extreme variations in feed heat value which in turn causes wide and uncontrollable temperature variations in the furnaces and results in refractory failures and air emission problems. Also, metals are usually not removed; therefore, hard objects are dragged across each hearth, causing erosion problems.

These problems were resolved in test work conducted at the Central Contra Costa Sanitary District operated wastewater treatment plant at Concord, Calif. All refuse was shredded, air classified and screened prior to use. This test work, when the furnace was operated in an incineration mode, showed none of the problems encountered in England or Europe except that temperature control was still difficult. This was corrected by operating the furnace in a pyrolysis (starved-air combustion) mode, described further under copyrolysis. Based upon European experience and the test work in Concord, coincineration of raw solid waste and sludge in a multiple-hearth furnace does not appear to be a viable process.

Copyrolysis Methods (Sludge and Municipal Refuse)

Partial pyrolysis and true pyrolysis have been applied by several furnace manufacturers to the combustion of solid waste, but there are only three partial pyrolysis systems (more correctly, starved-air combustion) that have been operated on sewage sludge and solid waste. Only one system, using the multiple-hearth furnace, used a sludge furnace with solid waste as the fuel source. The other systems are solid waste combustion systems modified to permit the addition of wet sludge. This basic difference allows the multiple-hearth furnace to operate on 100 percent sludge to 100 percent refuse, while the other systems must have a refuse-to-sludge wet ratio of at least 2:1. The key to any pyrolysis process is to add less air than is required for complete combustion in the reactor. The combustible gas produced in the reactor is fired in an afterburner, providing an efficient two-stage combustion process.

Multiple Hearth

Copyrolysis of sludge with processed municipal solid waste in an MHF was first successfully performed in a small-scale test in November 1974. Recognizing scale-up problems, a full-scale prototype test was implemented as described under "Sludge Pyrolysis" and further herein. A flow diagram of the test system is given on figure 7–12. The test MHF pyrolyzed a combination of sewage sludge

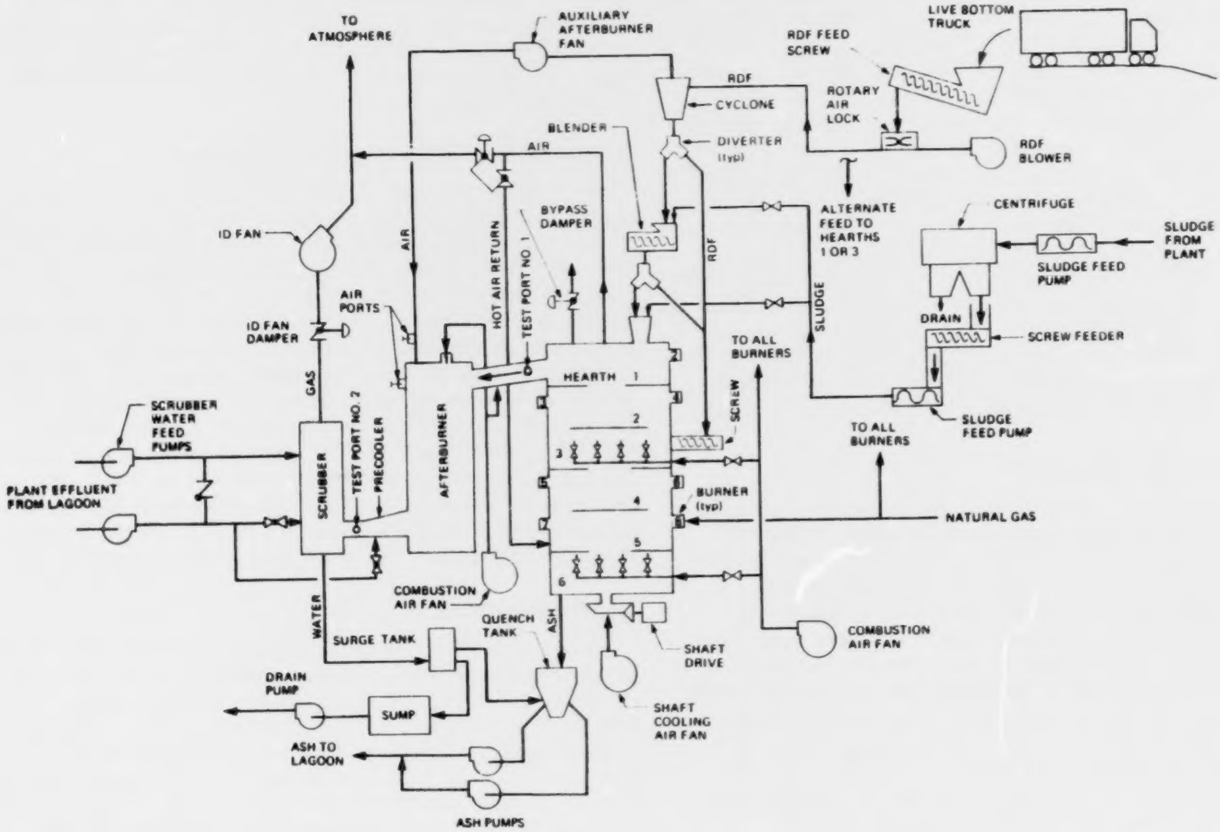

TO ATMOSPHERE
AUXILIARY AFTERBURNER FAN
LIVE BOTTOM TRUCK
RDF FEED SCREW
RDF
CYCLONE
ROTARY AIR LOCK
BLENDER
AIR
DIVERTER (typ)
RDF BLOWER
BYPASS DAMPER
ALTERNATE FEED TO HEARTHS 1 OR 3
CENTRIFUGE
ID FAN
AIR
HOT AIR RETURN
TEST PORT NO 1
RDF
SLUDGE FROM PLANT
SLUDGE FEED PUMP
AIR PORTS
SLUDGE
DRAIN
ID FAN DAMPER
TO ALL BURNERS
SCREW FEEDER
GAS
HEARTH 1
2
3
4
5
6
SCREW
SCRUBBER WATER FEED PUMPS
TEST PORT NO. 2
PRECOOLER
SCRUBBER
AFTERBURNER
TO ALL BURNERS
SLUDGE FEED PUMP
PLANT EFFLUENT FROM LAGOON
BURNER (typ)
NATURAL GAS
COMBUSTION AIR FAN
WATER
SURGE TANK
QUENCH TANK
ASH
SHAFT DRIVE
COMBUSTION AIR FAN
DRAIN PUMP
SUMP
SHAFT COOLING AIR FAN
ASH TO LAGOON
ASH PUMPS

Figure 7–12.—Central Contra Costa test project flow diagram.

and refuse-derived fuel (RDF) in several ratios from pure sludge to pure RDF.

Municipal refuse was shredded, air classified and screened to produce a refuse-derived fuel. The RDF had a heating value of 7,500 Btu (17,400 J/g) per pound of dry solids and a moisture content of 25 percent. A combined feed rate of up to 10,000 pounds (4,540 kg) per hour was applied to the 6-hearth, 18 ft 9 in. (5.71 m) diameter MHF. Because of the addition of RDF, the heat value of the feed was greatly increased as compared to sludge alone. This resulted in a fuel gas heat value averaging 136 Btu/sdcf (5066 kJ/m^3) and afterburner temperatures up to 2500°F. The furnace was controlled by regulating the addition of air to maintain hearth temperature. This approach proved to be a stable, dependable control system.

Significant results of the test, in addition to that noted under "Sludge Pyrolysis," include:

- RDF should be fed to a midfurnace hearth and sludge to the top or second hearth to maximize energy conversion.
- The ash handling system must be capable of handling small amounts of metal.
- Autogenous combustion of a 16 percent solids sludge cake could be accomplished with an RDF-to-sludge wet ratio of 1:2.

This type of system is being reviewed for several

Table 7–9.—Material and heat balance for copyrolysis of municipal refuse and sludge in a multiple-hearth furnace[a]

Stream	Alternate					
	IA 5 Mgal/d 20 percent solids	IB 5 Mgal/d 40 percent solids	IIA 15 Mgal/d 20 percent solids	IIB 15 Mgal/d 40 percent solids	IIIA 50 Mgal/d 20 percent solids	IIIB 50 Mgal/d 40 percent solids
Furnace design						
Diameter (ft–in.)	22–3	16–9	25–9	18–9	25–9	22–3
Number of hearths	6	7	6	8	9	8
Hearth loading rate (lb wet solids/sq ft/hr)	11.4	10.8	11.8	11.3	12.5	12.1
Sludge feed						
lb dry solids/hr	1,806	1,806	2,713	2,713	4,293	4,293
Percent of total furnace feed	50	50	50	50	50	50
Volatile content (percent)	77	65	77	65	77	65
RDF feed						
lb dry solids/hr	7,224	4,267	10,850	6,400	17,172	10,128
Percent of total furnace feed	50	50	50	50	50	50
Volatile content (percent)	84	84	84	84	84	84
Percent moisture	20	20	20	20	20	20
Combined feed rate						
Total lb wet solids/hr	18,060	10,664	27,126	16,000	42,930	25,320
Heat value (MM Btu/hr)	20.28	11.12	30.71	16.38	47.29	25.53
Total furnace inlet air (lb/hr)	12,753	7,320	19,316	10,782	29,747	16,806
Ash						
Volume (lb/hr)	1,749	1,589	2,627	2,384	4,158	3,772
Heat value (MM Btu/hr)	0.50	0.46	0.76	0.69	1.20	1.09
Afterburner inlet air						
Volume (lb/hr)	34,123	25,867	51,049	39,065	81,838	112,888
Afterburner exhaust						
Volume (lb/hr)	63,186	42,260	94,861	63,461	150,355	151,240
Heat value (MM Btu/hr)	62.45	40.80	92.39	61.29	146.05	97.68
Radiation						
Heat loss (MM Btu/hr)	1.62	1.12	2.33	1.61	3.57	2.45
Recoverable heat						
100 percent efficiency (MM Btu/hr)	33	29	60	37	100	60
Connected power						
Horsepower	555	343	725	418	725	555
Installed cost (MM dollars)	2.8	2.2	3.0	2.4	3.5	3.0

[a] All data supplied by the Eimco BSP Division of Envirotech Corp.

plants with implementation expected for the Central Contra Costa Sanitary District and the city of Memphis.

Energy and mass balances for copyrolysis of sewage sludge and RDF in an MHF are given in table 7–9 for the selected treatment plant alternative. The addition of RDF to sludge could provide for more efficient heat recovery, due to higher afterburner temperatures. This in turn could permit combustion of wet sludges without supplemental fuel.

Vertical Packed Bed

There are two vertical packed bed solid waste partial pyrolysis systems currently operating in the United States: Andco-Torrax and PUROX.

The Andco-Torrax system is a vertical furnace in which unprocessed municipal solid waste is charged into the system from the top. This ram of refuse provides a combustion seal. The refuse is burned at the bottom of the ram at 3000°F by the addition of small quantities of hot air heated by the afterburner exhaust. The combustible off-gases are afterburned at 2000°F and scrubbed by electrostatic precipitators. Wet sludge has been added to an existing 75-ton-per-day (68 Mg) system but no detailed test data are presently available.

PUROX, a Union Carbide process, is a vertical furnace pyrolyzing a processed refuse. Processing includes shredding and ferrous metal separation. The PUROX process uses pure oxygen rather than air. The refuse is combusted at 3000°F, and fuel gas very low in nitrogen with a heat value of 385 Btu/sdcf (14,340 kJ/m^3) is produced. The slag produced at the high combustion temperature is primarily silica and is inert. A test pyrolyzing processed refuse and sludge was sponsored by EPA and successfully run on the test unit at South Charleston, W. Va., for 2 months. Daily average wet test feed rates were 90 tons (82 Mg). The test report has been submitted to EPA for review but has not yet been published. Significant test results include:

- A refuse to sludge ratio of 4.26:1 was pyrolyzed. Lower ratios were not tested due to the limited availability of sludge.
- Pure oxygen feed rate was approximately 0.2 ton (0.2 Mg) of oxygen per ton (0.9 Mg) of feed.
- Fuel gas production and quality, and slag production and quality do not differ radically from refuse pyrolysis.
- Heavy metals in the sludge were found to be trapped in the slag and not discharged via the exhaust gases.

Institutional Constraints

Coincineration and copyrolysis of sewage sludge with municipal solid waste is a viable, cost-effective, and socially beneficial approach to the solids handling problem. Not only are both solid waste streams disposed in an environmentally acceptable manner, but benefits can be accrued by utilizing the waste heat or combustible exhaust gases for energy conservation. Although the technical feasibility of copyrolysis and coincineration of sludge and solid waste has been demonstrated, there remain a number of institutional constraints that may have to be resolved prior to implementation of a codisposal project.

In many localities in the country, wastewater treatment and solid waste disposal are controlled by different governmental agencies. Many communities have contracts with private firms for refuse handling and disposal which release ownership of the refuse to the contractor. Some of the contracts are long-term, lasting 15 to 20 years. Although there have been legal opinions that these agreements can be modified for the benefit of the public, these opinions have not been tested in court. In recent waste disposal contract negotiations, local governments have retained the ownership of the refuse with the private firm acting strictly as a collector and hauler. Retaining ownership of the waste material would simplify resource recovery operations.

Consolidation of the governmental agencies which are responsible for solid and liquid waste disposal would also simplify disposal operations; however, with more emphasis on codisposal techniques by both federal and state agencies, serious institutional problems may be resolved by governmental interaction with local agencies. Jurisdictional disputes could prove to be more of an impediment than technical difficulties of the codisposal process.

Funding

Funding of codisposal projects is a very complex issue because several federal, state, and local agencies are involved and there are many departments within these agencies which can also fund projects. To further complicate the total project funding picture, the ownership of the nonsewerage facilities (municipal solid waste, industrial wastes, etc.) can be either public or private. Because of this, EPA has developed a memorandum, PRM #77-4, entitled "Cost Allocation for Multiple Purpose Projects."

While this memorandum has been used in recent projects to determine fundable costs, some projects cannot be distributed equitably by this method due to a complicated cost distribution formula, impact of operation and maintenance costs, and the basic philosophy differences between a single-purpose and a multiple-purpose project. For instance, if solid waste is used to combust sludge when no solid waste problem exists, is there a solid waste savings as defined by the memorandum? This memorandum is not a regulation or a guideline but simply one method which may be used.

A few states have instituted guaranteed loan programs for bonding solid waste projects and some financial consultants are beginning to specialize in solid waste project funding. Also, several solid waste equipment manufacturers have designed, built and operated large resource recovery solid waste projects to produce RDF and recover metals.

The method and type of funding for these cocombustion projects appears very open but obtaining the funds demands considerable time and effort.

AIR POLLUTION CONSIDERATIONS

In any combustion system, air emissions are a major concern and may be the most difficult and costly regulations to satisfy. On the federal level, EPA has established standards of performance for municipal incinerators (solid waste) and sewage sludge incinerators. In cocombustion schemes involving municipal solid waste and sewage sludge, both standards will probably apply with each being prorated on a Btu feed basis. In January 1978, EPA published proposed emission standards of performance for new, modified or reconstructed electric utility steam generating units that burn fossil fuel or a combination of fossil fuels and other fuels, e.g., solid wastes. These guidelines offer some indication of air pollution requirements in cocombustion schemes.

Generally, new sludge furnaces will have to comply with the following federal standards:

- National Ambient Air Quality Standards.
- National Emission Standards for Hazardous Air Pollutants, subparts A and E.
- Standards of Performance for New Stationary Sources, subparts A, O and probably E if cocombustion is proposed.
- New Source Review Rule
- Regulations Pertaining to Prevention of Significant Deterioration of Air Quality.

A basic problem in evaluating any emission is predicting the effect on the overall air basin. Projecting emission and the resulting air quality is, at best, an imperfect science. Air basins in which critical air quality levels are consistently exceeded have been studied in depth and have been the object of mathematical modeling. The results of these efforts have been mixed.

National Ambient Air Quality Standards (NAAQS)

Federal air quality regulations are derived from the Clean Air Act Amendments of 1970, the Energy Supply and Environmental Coordination Act of 1974, and most recently, the Clean Air Act Amendments of 1977. The NAAQS are designed to protect public health and welfare and are established at threshold levels below which no adverse effects would occur. Air pollutants are divided into two groups: primary pollutants and secondary pollutants. Primary pollutants are those emitted directly from sources, while secondary pollutants are formed by chemical and photochemical reactions in the atmosphere. Primary pollutants include carbon monoxide (CO), hydrocarbons (organic gases), oxides of nitrogen (NO_x), sulfur dioxide (SO_2), and total suspended particulates (TSP). Photochemical oxidants and nitrogen dioxide (NO_2) are the principal secondary pollutants. Nitrogen dioxide is the visible brown-yellow haze. The formation of secondary pollutants is dependent upon the availability of sunlight as much as the emission of primary pollutants that are converted to secondary pollutants. Health effects of contaminants are summarized in table 7–10. Federal primary standards are to be achieved in 1977 and secondary standards in a reasonable period of time, whereas state standards are considered goals without a specified time for compliance.

The 1970 Amendments to the Clean Air Act require the States to develop implementation plans to meet the Federal standards by 1975 or 1977, depending on the severity of the State's air quality problems. The 1977 Amendments have delayed attainment deadlines and have detailed some appropriate control measures. For "nonattainment areas," those which have not yet attained NAAQS, states must have an approved implementation plan revision by July 1, 1979, which provides for attainment by December 31, 1982. If a State cannot obtain primary standards for carbon monoxide or photochemical oxidants, it must submit a second plant revision by December 31, 1982, which provides for attainment by December 31, 1987. For areas which are cleaner than NAAQS, implementation plans must include a program to prevent significant deterioration of air quality. EPA guidelines require the implementation plans to provide for emission controls, transportation controls, source monitoring, ambient air quality monitoring, and a procedure for review and approval of new sources of air pollution prior to construction. EPA has the authority to approve or disapprove these plans and to promulgate an acceptable plan if the submitted plan is disapproved. EPA, state air resources boards, and local air pollution control districts also have the authority to restrict issuance of permits for construction of stationary sources if emissions from that source would cause the violation of any air quality standard. In both nonattainment and nondegradation areas, major stationary sources may be constructed only by permit and must at least meet new source performance standards.

National Emission Standards for Hazardous Air Pollutants (NESHAPS)

Subpart A of NESHAPS comprises general provisions covering definitions, applications, reporting and waivers. Subpart E deals with mercury and applies to all operations that burn or dry sewage sludge. The NESHAPS standard (*Federal Register,* vol. 40, No. 199, Tuesday, October 14, 1975) is currently 3,200 grams or 7 pounds of mercury per 24-hr period. Beryllium is also controlled, and several other air contaminants such as lead and PCB are currently under study for possible inclusion into NESHAPS.

Standards of Performance for New Stationary Sources (NSPS)

Subpart A of NSPS involves general provisions covering definitions, performance tests, authority, monitoring requirements, etc. Subpart A is applicable to all incinerators with a charging rate greater than 50 tons (45 Mg)

Table 7–10.—Health effects of air pollutions

Air quality level	Pollutant levels					Health effect descriptor	General health effects	Cautionary statements
	TSP (24-hour), $\mu g/m^3$	SO_2 (24-hour), $\mu g/m^3$	CO (8-hour), mg/m^3	O_3 (1-hour), $\mu g/m^3$	NO_2 (1-hour), $\mu g/m^3$			
Significant harm..........	1,000	2,620	57.5	1,200	3,750	Hazardous	Premature death of ill and elderly. Healthy people will experience adverse symptoms that affect their normal activity.	All persons should remain indoors, keeping windows and doors closed. All persons should minimize physical exertion and avoid traffic.
Emergency................	875	2,100	40.0	1,000	3,000	Hazardous	Premature onset of certain diseases in addition to significant aggravation of symptoms and decreased exercise tolerance in healthy persons.	Elderly and persons with existing diseases should stay indoors and avoid physical exertion. General population should avoid outdoor activity.
Warning....................	625	1,600	34.0	800	2,260	Very unhealthful	Significant aggravation of symptoms and decreased exercise tolerance in persons with heart or lung disease, with widespread symptoms in the healthy population.	Elderly and persons with existing heart or lung disease should stay indoors and reduce physical activity.
Alert........................	375	800	17.0	[a]400	1,130	Unhealthful	Mild aggravation of symptoms in susceptible persons, with irritation symptoms in the healthy population.	Persons with existing heart or respiratory ailments should reduce physical exertion and outdoor activity.
NAAQS	260	365	10.0	160	[b]—	Moderate		
50 percent of NAAQS ..	[c]75	[c]80	5.0	80	[b]—	Good		
	0	0	0	0	[b]—			

[a] 400 $\mu g/m^3$ was used instead of the O_3 Alert Level of 200 $\mu g/m^3$ (see text).

[b] No index values reported at concentration levels below those specified by "Alert Level" criteria.

[c] Annual primary NAAQS.

Source: EPA, Environmental News, August 23, 1976.

per day with municipal refuse comprising more than 50 percent of the charge. Subpart E requires that particulates discharged be no greater than 0.08 grain/sdcf (0.18 g/m³), corrected to 12 percent carbon dioxide. Subpart O is applicable to incinerators that burn municipal sewage sludge and requires that particulates discharged cannot be in excess of 1.30 pounds (0.65 kg/Mg) per ton of dry sludge feed and that the gas discharged shall not have more than 20 percent opacity.

New Source Review Standards (NSR)

This regulation, 40 CFR 52.18, requires a preconstruction review of all stationary sources to determine if the source will meet all applicable emission requirements of the State Implementation Plans.

The reviewing authority is usually a state agency which can apply more strict emission standards than the EPA regulations. In areas where the NAAQS is being violated, emission trade-offs, or offsets, in the air basin may be required prior to acceptance of the new source.

Prevention of Significant Deterioration (PSD)

Federal Regulation, 40 CFR 52.21, limits increases in particulate and sulfur dioxide concentrations above base levels measured in designated areas. Data on total emissions for the entire air basin are required to evaluate incremental increases in specific emissions due to operation of any new furnaces.

SYSTEM DESIGN

Determining the feasibility of a solids disposal system entails the review of many components of the system. Each acceptable solids disposal system must meet all environmental constraints while being an economical and feasible system. In evaluating the effectiveness of a furnace system, important considerations are:

- Sludge quantity and quality.
- Installed cost of the equipment.
- Method and cost of housing the system.
- Local air pollution requirements.
- Methods of funding.
- Supplemental fuel costs including start-up fuel, standby fuel, fuel availability, etc.
- Pretreatment options.
- Operation and maintenance costs.
- Ash disposal options and costs.
- Equipment redundancy requirements.
- Type of operation, continuous or intermittent.
- Emergency methods of sludge handling.
- Institutional constraints.

Many other detailed design considerations must be analyzed as set forth previously in this paper. Heat recovery must be analyzed in any combustion process. There are no strict guidelines to the review of a furnace system, but experience and review of existing systems with a consultation of various equipment manufacturers provide an excellent foundation.

DESIGN EXAMPLES

Two design examples are presented to demonstrate some of the principles introduced in this paper. The first example involves the selection of an incineration system to replace the existing sludge handling system at a small wastewater treatment plant. The second example considers retrofitting an existing multiple-hearth furnace in a large municipal wastewater treatment plant to meet changing values of plant capacity, air emissions, fuel cost and fuel availability.

Design Example 1: New Sludge Incineration System

The first design example involves a small treatment facility with a sludge handling system that must be revised to minimize increasing disposal costs.

Problem Statement

A municipal wastewater treatment plant with an average daily flow of 5 Mgal/d (0.22 m^3/s) must modify its present solids handling and disposal method. The plant uses a conventional activated sludge process with anaerobic digestion of combined primary sludge, waste activated sludge, and scum. The digested sludge is vacuum filtered and is hauled to the local landfill which is scheduled to close shortly. The new disposal location must limit the water discharged to the site and is several miles from the treatment plant. These conditions result in extremely high disposal costs. Onsite disposal options are limited because the area surrounding the plant has been heavily developed by meat packing and rendering operations. These industries discharge significant amounts of animal greases and oils to the treatment plant and are concerned about finding an economical solution to the sludge disposal problem because of the large industrial sewer service charges. Most of the industrial wastes discharged to the plant are removed in the primary tanks and result in a combined scum and sludge with an extremely high heating value. The basic plant data are shown in table 7–11.

Approach

The city hired a consultant to evaluate several disposal methods including land disposal, composting, heat treatment, combustion and continuation of the present operation. A cost-effective solution was identified to be combustion due to the high energy content of the sludge and the limited available land for sludge disposal. Digestion would be eliminated so that the full heat value of the sludge could be utilized in combustion eliminating all supplemental fuel requirements. The existing digesters would be converted to sludge thickening/storage units

Table 7–11.—Design Example 1: wastewater treatment plant operating data

Parameter	Value
Plant flow, Mgal/d	5
Sludge to disposal, lb/day dry basis	10,320
Solids heat value, Btu/lb dry basis	11,000
Volatile solids to digester, percent of dry solids	77
Sludge solids content, percent solids by weight	20
Vacuum filter operation, hr/week	40

with the existing vacuum filters remaining to provide an incinerator feed solids content of approximately 20 percent.

Presently, the vacuum filter operates 6 to 8 hours a day, 5 days a week. Due to the limited plant area, there is no room for filter cake holding facilities and the furnace will therefore be designed to operate in conjunction with the vacuum filters. A review of the various furnace systems indicated that because of the high heating value of the sludge, the intermittent operation requirement and the space limitations, a fluid bed furnace would be the most cost- and energy-effective furnace solution.

Preliminary Design

The data in table 7–12 were given to experienced fluid bed furnace manufacturers for analysis including heat and material balances. Table 7–13 was provided by the manufacturers and shows all sizing criteria as well as requirements for peripheral equipment. For intance, 416 dry lb (188.7 kg) per hour of ash must be disposed for each hour of furnace operation. The amount of ash storage, ash truck size, and frequency of runs to the landfill can be calculated from this number based upon site specific constraints including the method of ash dewatering. Also, the amount of scrubber water recycled to the plant is shown so the extra load to the liquid waste stream can be determined.

As is evident herein, the detailed design of the complete system actually starts with the data provided by the furnace manufacturer. Air emissions must be studied and submitted to the local, state and federal authorities to obtain a permit to construct. Contracts for ash disposal should be developed to assure continued, dependable and economic disposal sites. Options for using available excess heat should also be examined. Table 7–13 shows 6.0 MMBtu per hour (1,758,000 W) are available for use; however, this is an intermittent heat availability and intermittent demands are difficult to determine. As an example, since the day shift staffing of the plant is the largest, space heat and cooling loads would be larger during the day. To satisfy off-peak demands, heated and chilled water storage vessels may be economical rather than providing auxiliary fired boilers.

Table 7–12.—Design Example 1: sludge furnace design criteria

Parameter	Value
Sludge feed	
Solids content, percent by weight	20
Volatile solids content, percent of dry solids	77
Heat value, Btu/lb of dry solids	11,000
Furnace operation, hr/week	40
Average solids loading rate, lb/hr, dry basis	1,810

Table 7–13.—Design Example 1: heat and material balances for a fluid bed furnace

Stream, unit	Value
Furnace design	
Inside diameter, ft–in.	15.0
Loading rate, lb wet solids/sq ft/hr	51.2
Sludge feed	
lb dry solids/hr	1,810
Heat value, MMBtu/hr	19.91
Volatile solids, percent dry solids	77
Supplemental fuel	0
Combustion air	
Volume, lb/hr	22,950
Heat value, MMBtu/hr	5.40
Ash	
Volume, lb/dry solids/hr	416
Heat value, MMBtu/hr	0.12
Water flow, gal/min	20
Radiation	
Head loss, MMBtu/hr	1.27
Recoverable heat	
100 percent efficiency, MMBtu/hr	[a]6.0
Recuperator	Yes
Venturi water	
Recycle water, gal/min	94
Makeup water at 70° F, gal/min	5
Scrubber water feed	
Flow at 70° F, gal/min	397
Scrubber water drain	
Flow at 130° F, gal/min	410
Gas exhaust	
Volume, ACFM	6,162
Temperature, °F	120
Connected power, hp	240
Startup fuel requirements	
Weekday operation, 16-hour shutdown, MMBtu/hr	0
Monday morning operation, 64-hour shutdown, MMBtu/hr	[b]0.42

[a] At 1,400° F.

[b] Fuel required:
1 hour on Saturday.
1 hour on Sunday.
1/2 hour on Monday morning.

Data supplied by Dorr-Oliver Inc.

Other design considerations to be investigated would include but are not limited to:

- Scrubber and quench water quality, i.e., is secondary effluent quality sufficient?
- Effect of scrubber return water on treatment plant operation (quality, quantity and temperature).
- Expected ash quality.
- Ash dewatering methods.
- Ash hauling methods: by city, by separate contract, by other city departments.
- Type of sludge conveyors.
- Type and location of fans.

- Heat recovery methods.
- Electrical distribution.
- Control philosophy.
- Sophistication of instrumentation and control.
- Supplemental fuel availability and storage (for start-up and problem periods).
- Area clearance including access platforms.
- Housing the furnace, i.e., is a building needed?
- Structural requirements: seismic, wind, etc.
- Noise levels and other OSHA requirements.
- Heating, ventilating and cooling the area near the furnace.
- Spare parts.
- Level and quality of staffing.

These points only relate to the installed system. Other important considerations involve the interfacing of the existing plant with the construction of the furnace. For instance, it may be economically attractive to dispose of the digested sludge at the plant in the furnaces prior to converting the digesters to thickeners or there may be site-specific scheduling problems. If the digested sludge will be burned, this should be a part of the contract documents in case minor additions are required. In any case, all systems and details relating to the furnace should be discussed with the furnace manufacturer and, in some cases, made the responsibility of the furnace manufacturer, e.g., the combustion air fans, the recuperator (if used), the heat recovery boiler (if used), scrubbers, and some or all of the controls.

Design Example 2: Retrofit of an Existing Multiple-Hearth Sludge Incinerator

This example involves retrofitting an existing sludge incineration system to accommodate more stringent air emission regulations and increasing quantities of sludge due to area growth.

Problem Statement

A 20-Mgal/d (0.88 m^3/s) domestic wastewater treatment plant in the Midwest has been incinerating primary and excess activated sludge in two multiple-hearth furnaces. All sludge is thickened prior to dewatering on vacuum filters which provide a 25 percent solids feed cake. Polymers are used in the vacuum filters. The ash from the furnaces is sluiced to ash holding ponds and the supernatant is recovered and returned to the plant sewer. Stabilized ash is clammed at least once a year and hauled to the local landfill.

Both multiple-hearth furnaces are used simultaneously about 3 months of the year as the original design provided 100 percent redundancy and the plant is currently overloaded for a portion of the year.

The growth in the present service area has been reduced in recent years to an E-O level, approximately 2 percent; however, the city is planning to annex several more surrounding areas in the immediate future. Due to the present overloaded conditions, anticipated growth, and service area increases resulting in increased flows, planning for a 10-Mgal/d (0.44 m^3/s) expansion is currently underway which would provide for projected flows through 1988. In addition, new air emission regulations were recently promulgated limiting hydrocarbon, carbonyl and carbon monoxide emissions to about half of the current incinerator emissions. The city has been given notice to correct this situation shortly or the local air pollution control district (APCD) will begin levying fines. The city has applied for and received a time extension to review and correct this problem. The existing plant data are shown in table 7–14.

Approach

The city had retained a consultant to prepare a facilities plan/project report to obtain funding for the expansion to 30 Mgal/d (1.31 m^3/s) under the Clean Water Grant Program. Due to the urgency of the experts air emissions problem, the city had its consultant hire air pollution experts to assist in the development of an interim plan which would be consistent with the goals of the expansion. The basic intent was that all interim emission control measures could be used in the expanded facilities, therefore possibly affording grant funding for the interim facilities.

Several methods for reducing critical emissions were reviewed and after detailed design studies, including cost estimates, afterburning at 1200°F for 1/2 second was determined to be the most cost-effective solution which could guarantee a continuous and dependable operation while satisfying all regulations.

Since afterburning was proposed, it was also decided to study starved air combustion (SAC) which could possibly increase the furnace capacity and/or reduce the equipment to be added. Prior to reviewing SAC, it was determined that each furnace would require an afterburner and that a new furnace and afterburner would be required for the plant expansion to 30 Mgal/d (1.31 m^3/s).

Table 7–14.—Design Example 2: existing wastewater treatment plant operating data

Parameter	Value
Treatment plant operating conditions	
Design flow, Mgal/d	20
Total solids, lb/day dry basis	40,800
Volatile solids, percent of dry solids	75
Furnace operating conditions	
Operating hours/week	168
Loading rate, lb/hr dry basis	1,700
Solids content of feed, percent dry weight	25
Loading rate, lb/hr wet basis	6,800

Table 7–15.—Design Example 2: heat and material balances for multiple-hearth furnaces

Type of operation	Existing condition	Case I	Case II	Case III	Case IV
	Combustion	Modified combustion	SAC[a]	SAC[a]	SAC[a]
Furnace design					
Number of furnaces	2	[b]3	[b]3	[b]2	[b]2
Diameter, ft–in	16–9	16–9	16–9	16–9	16–9
Number of hearths	7	7	7	7	[c]7
Hearth loading rate, lb wet solids/sq ft/hr	7.0	7.0	7.0	10.2	10.2
Afterburner	None	External	External	External	Internal (top hearth)
Sludge feed					
lb dry solids/hr	1,700	1,700	1,700	3,473	2,957
Heat value, MMBtu/hr	12.75	12.75	12.75	26.05	22.18
Volatile solids, percent dry solids	75	75	75	75	75
Feed solids, percent	25	25	25	35	35
Afterburner supplemental fuel, lb/hr					
Heat value, MMBtu/hr	0	3.77	2.44	0	0
Temperature, °F	60	60	60	60	60
Furnace combustion air					
Volume, lb/hr	17,833	17,833	9,822	12,507	9,867
Shaft cooling air					
Volume, lb/hr	15,939	15,939	15,939	15,939	15,939
Shaft cooling air return to furnace					
Volume at 350° F, lb/hr	13,548	13,548	9,840	12,480	9,867
Shaft cooling air to stack					
Volume at 350° F lb/hr	2,391	2,391	5,919	0.0	0
Heat value, MMBtu/hr	0.35	0.35	1.09	0.0	0
Shaft cooling air to afterburner					
Volume at 350° F, lb/hr	0	0	180	3,660	6,072
Ash					
Volume, lb/hr	425	425	[d]478	[d]975	[d]866
Heat value, MMBtu/hr	0.04	0.04	0.14	0.28	0.25
Radiation					
Heat loss, MMBtu/hr	0.29	0.29	0.29	0.29	0.29
Furnace exhaust					
Volume at 800° F, lb/hr	24,209	24,209	16,145	21,454	17,448
Heat value, MMBtu/hr	12.07	12.07	11.23	14.87	10.55
Afterburner combustion air					
Volume at 60° F, lb/hr	N.A.	2,555	4,296	11,534	10,989
Afterburner exhaust					
Volume, lb/hr	N.A.	26,764	19,366	32,987	28,437
Temperature, °F	N.A.	1,200	1,200	1,430	1,200
Heat value, MMBtu/hr	N.A.	15.84	14.05	24.24	21.64
Boiler exhaust					
Heat value at 400° F, MMBtu/hr	N.A.	9.51	8.78	13.92	4.58
Recoverable heat					
100 percent efficiency, MMBtu/hr	3.20	6.33	5.27	10.32	6.13
Precooler and Venturi water feed					
Flow at 70° F, gal/min	51	51	45	65	65
Scrubber water feed					
Flow at 70° F, gal/min	243	243	282	456	456
Scrubber drain					
Flow, gal/min	306	306	338	536	532
Gas exhaust					
Volume, lb/hr	21,368	20,759	15,480	26,220	27,837
Temperature, °F	120	120	120	120	120
Heat value, MMBtu/hr	6.35	7.53	4.11	8.52	2.64

N.A.—Not applicable.

[a] SAC—Starved air combustion.

[b] Number of furnaces required in 1988, 30 Mgal/d for increased sludge quantities with one furnace on standby.

[c] Note, top hearth is afterburner, therefore, not included in hearth loading calculations.

[d] Includes fixed carbon and volatile heat content.

Preliminary Design

The data in table 7–14 was given to experienced multiple-hearth furnace manufacturers for analysis including detailed heat and material balances for incineration followed by external afterburning and starved air combustion followed by external afterburning. Both cases used the present sludge dewatering method, vacuum filters, which provided a feed cake of 25 percent solids. Two additional cases were studied using improved dewatering equipment to give a feed cake solids of 35 percent. These cases both used starved air combustion but one had an external afterburner and the second used the top hearth of the present furnace as the afterburner. Capacities of the systems using the existing furnace(s) were required.

Table 7–15 was provided by the manufacturers and shows some very significant comparisons of incineration versus SAC and the effect of improved dewatering. For instance, converting the existing furnace to SAC with an external afterburner would save 1.53 MMBtu/hr (448,000 W) as compared to adding an afterburner to the present incinerators. This would result in an annual savings of slightly over $30,000 which, in this case, would not justify the conversion, especially since the recoverable heat from SAC would be less than incineration due to the lower exhaust volumes.

A significant advantage is shown for case IV where the top hearth of the existing furnace is used as an afterburner resulting in large cost savings by not requiring a separate afterburner. Also, by improving the dewatering methods, the existing system would easily handle the expected sludge loads through 1988, the design year.

The fuel savings would result in an annual reduction of plant operation expenses by almost $100,000 and the energy generated would be sufficient to save another $50,000 per year. These savings alone would justify capital expenditures of over $1,500,000. In addition there would be a capital savings which would occur because the addition of a third furnace would not be required.

After receiving detailed cost estimates, the city proceeded with the design of case IV. As noted in the previous design example, the detailed design effort begins with the data provided by the manufacturer. Details for necessary furnace modifications for conversion to SAC were noted earlier in the paper and other design details are similar to those discussed in Design Example 1.

SUMMARY AND CONCLUSIONS

The ultimate disposal of wastewater treatment plant sludges is a complex problem. New and emerging technologies in incineration, pyrolysis and starved air combustion are providing solutions for the safe, clean, efficient and inexpensive reduction of sewage sludge. Use of alternate fuel sources in coincineration and copyrolysis can provide excess energy which can be converted to steam for use within the treatment plant or for sale, all while reducing overall plant operation and maintenance costs.

Although many systems are still in the research and development stage, systems similar to those tested by the Central Contra Costa Sanitary District at Concord, Calif., and by the city of Franklin, Ohio, can be implemented using current technology and existing equipment.

ACKNOWLEDGMENTS

Credits

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Chapter 8

Sewage Sludge Composting

INTRODUCTION

Most of the early work on composting was concerned with composting municipal refuse. The University of California, Michigan State University and the U.S. Public Health Service were among the first to conduct basic studies on composting in the United States.[1,2] Two federally supported, large-scale research and demonstration projects were initiated in the United States at Johnson City, Tenn., and Gainesville, Fla. The Johnson City project investigated the open-windrow method of composting, whereas Gainesville employed a high-rate mechanical digester. These large-scale studies confirmed the technical feasibility of composting domestic municipal refuse and the lack of economic viability.[3] The paper by Wiles[3] also contains a brief historical review of solid waste composting.

Sewage sludge composting is a relatively recent development in the United States. The Eimco Corp. conducted a study in 1967 to 1969 for the U.S. Public Health Service on composting primary sludge from the Salt Lake City Sewage Treatment Plant.[4] In a project supported by EPA, the U.S. Department of Agriculture, Agricultural Research Service (USDA) in cooperation with the Maryland Environmental Service and the Blue Plains Wastewater Treatment Plant began investigating sludge composting in 1972.[5] This project is located on the grounds of the USDA Agricultural Research Center at Beltsville, Md., and the studies have demonstrated new techniques in sewage sludge composting.[6,7] Sludge composting studies and demonstration projects are also in progress at Bangor, Maine;[8] Durham, N.H.; and the Los Angeles County Sanitation Districts, at Carson, Calif.

Composting of wastewater sludge differs significantly from composting solid wastes. There are several advantages of composting sewage sludge compared to solid waste and the past poor publicity and problems associated with solid waste composting need not discourage the use of composting as an alternative in the treatment and reuse of wastewater sludge.

1. Composting solid wastes requires a complex materials handling and separation process that is not necessary in sludge composting.
2. Solid wastes vary widely in composition and as a result the composting process is usually more difficult to operate than a sludge composting system.
3. Several past solid waste composting operations were evaluated on the basis of their profit making potential rather than as an alternative disposal method.
4. The per capita quantity of solid waste is several times the wastewater sludge quantity; therefore, marketing or disposal of solid waste compost is a more difficult task.
5. Sewage sludge compost is a more uniform product because plastics, metals and other materials often remain in solid waste compost.

Present day composting is defined as the aerobic thermophilic decomposition of organic solid wastes to a relatively stable humus like material.[9] The basic composting mechanisms are similar for any organic material and are described in more detail in several publications.[10,11] Modern composting actually involves both mesophilic and thermophilic temperatures, and, since it is a biological process, is subject to the constraints of any biological system. Decomposition is accomplished by various microorganisms including bacteria, actinomycetes and fungi. The principal byproducts of this aerobic decomposition are carbon dioxide, water and heat.

Proposed sludge regulations in California define sludge composting as follows:

> Compost means to process dewatered sludge in a manner that (a) exposes all portions of the sludge to air and to a temperature at least 60 degrees centigrade for at least 48 hours; (b) subsequently reduces the water content of the sludge to 40 percent or less, by weight; and (c) sufficiently decomposes the sludge so that it will not produce excessive odor or reheat above 40 degrees centigrade in the center of a pile that is one meter high, one meter wide, and one meter long, in a test wherein the sludge is remoistened to a water content of 55 percent, by weight and held for four days, after having undergone steps (a) and (b) above.

Sludge compost is a natural organic product with high humus content similar to peat. It has a slight musty odor, is moist, dark in color, can be bagged; the texture varies depending on the degree of screening. Compost increases the water holding capacity of sandy soils, improves the structure of heavy clay soils, and increases the air content of the soils. The organic matter in compost improves the workability of the soil and makes it easier for plant roots to penetrate. Compost contains small amounts of nitrogen, phosphorus and potash; therefore, its primary usefulness is as a soil amendment and not as a fertilizer. The typical compositions of sludge and compost produced at Beltsville, Md., and Bangor, Maine, are shown in tables 8–1a and 8–1b.

Table 8–1a.—Average composition of sludge and compost, Beltsville, Md.[a]

	Digested sludge	Screened compost
Dewatered filter cake		
Water	80	35
Total solids	20	65
Solid fraction		
Organic matter	50	50
Nitrogen	2.5	0.9
Phosphoric acid	2.7	2.3
Potash	0.6	0.2
Sulfur	0.9	0.4
Calcium	2.9	2.6
Magnesium	1.0	0.3
Boron	23 ppm	27 ppm
Heavy metals		
Zinc	2,000 ppm	1,000 ppm
Cadmium	19 ppm	9 ppm
Copper	600 ppm	250 ppm
Lead	540 ppm	320 ppm
Microorganisms, MPN/100 g		
Total coliforms	23,000,000,000	97,000
Fecal coliforms	2,400,000,000	3,000
Salmonella	6,000	0

[a] Percent by weight except where noted.

Table 8–1b.—Average composition of sludge and compost, Bangor, Maine

Constituent	Pile A[a]		Pile B[a]	
	Sludge mg/kg	Screened compost[b] mg/kg	Sludge mg/kg	Screened compost[b] mg/kg
Total sulfide	121.8	0.5	192.7	0.5
Total phosphorus	3,002.2	1,010.7	2,052.6	787.3
Total chloride	661.8	694.4	718.2	762.3
Total nitrogen	19,350.0	8,620.0	10,710.0	6,850.0
Cadmium	4.78	0.67	0.92	0.58
Copper	277.7	83.9	167.3	32.2
Chromium	28.6	17.0	33.4	10.0
Mercury	93.12	1.46	19.02	0.97
Nickel	22.6	25.2	34.8	19.2
Lead	408.0	118.1	274.2	64.2
Zinc	453.0	153.7	282.0	98.3
Iron	7,550.0	4,173.0	13,708.0	3,041.0
Arsenic	0.39	0.26	1.73	0.20
Manganese[c]	110.7	779.7	295.0	616.0
Potassium[c]	1,015.0	1,946.0	1,725.0	1,683.0
Calcium[c]	14,429.0	23,689.0	12,986.0	18,163.0
Magnesium[c]	2,198.0	3,602.0	4,525.0	3,066.0
Sodium[c]	234.9	698.0	373.9	274.9

[a] The sludge used in pile A and that used in pile B came from separate batches processed through the sewage treatment plant more than 6 months apart.

[b] One inch mesh screen.

[c] Increases noted in manganese, potassium, calcium, magnesium, and sodium are due to the bark in the compost.

COMPOSTING SYSTEMS

General Process Description

The composting process may be physically achieved in basically three types of systems: (1) windrow, (2) aerated static pile, and (3) mechanical units of various designs which usually supply continuous mixing and positive aeration. The windrow and static pile methods have been used almost exclusively for composting sewage sludge in the United States.

The basic steps in both the windrow and static pile composting systems are similar and are illustrated in the process flow diagram in figure 8–1. Several mechanical composting systems are described later in this paper. The sequential steps in the windrow and static pile methods are as follows:

1. Dewatered sludge is delivered to the site and usually mixed with a bulking agent. The purpose of the bulking agent is to decrease the moisture content of the mixture, increase porosity of the sludge and assure aerobic conditions during composting. Various bulking agents can be used including wood chips, bark chips and rice hulls. Unscreened finished compost has also been used. Generally, one part sludge is mixed with two to three parts bulking agent.
2. Piles are constructed by placing the sludge-bulking agent mixture in windrows or static piles.
3. Piles are aerated for 21 to 30 days by mechanically turning (windrow method) or by forced aeration (static pile method). Oxygen levels are maintained in the range of 5 to 15 percent of gas volume to assure aerobic conditions. Temperatures in all parts of the pile should be maintained at 60° C or above for at least 48 consecutive hours.
4. Piles are dismantled and the sludge-bulking agent mixture moved to a curing area for an additional 30 days. Curing provides time for additional stabilization and drying. The curing piles are not mechanically aerated.
5. The sludge-bulking agent mixture (compost) is screened to recover and reuse the bulking agent. It may be possible to screen the mixture before curing if it has dried sufficiently to permit screening and to prevent the development of anaerobic conditions. About 70 to 75 percent of the wood and bark bulking agents have been recovered in opera-

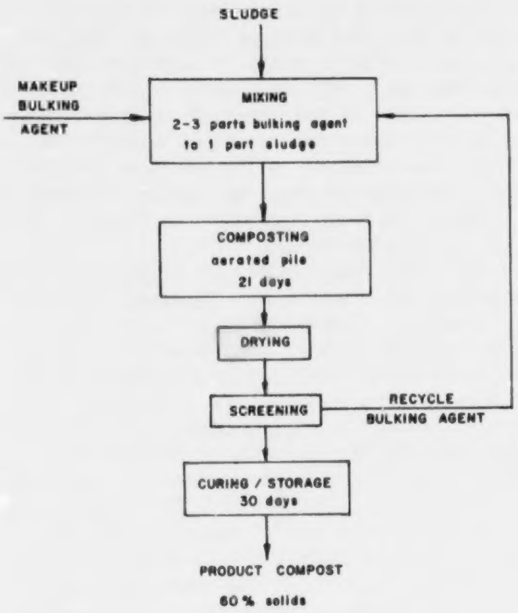


Figure 8–1.—Aerobic composting.

tions at Beltsville and Bangor. The finished compost can then be used or stored.

Research at the University of California and other locations developed some fundamentals of composting and these are summarized by Golueke.[10,11]

1. Obtaining thermophilic temperatures requires no input of external energy when the composting mass is sufficiently insulated and favorable environmental conditions are maintained for the biological organisms.
2. No inoculation with external microbial cultures is necessary either before, during or after the composting process.
3. The relations between environmental factors and the course of the process are characteristic of any biological process.

The net result of the composting process is the partial stabilization of organic material. Sludge is not completely stabilized or rendered inert by composting because this would result in end products of carbon dioxide, water and mineral ash. Obviously this is not possible nor desirable in a composting system. The desired degree of stability is one in which the product will not give rise to nuisances when stored even if moisture is added. It was observed in studies at the University of California that attainment of a satisfactory degree of stabilization was always accompanied by a final decline in temperature: once the temperature had declined to about 45 to 50° C the material was sufficiently stabilized to permit indefinite storage.

Composting is a dynamic process representing the combined activity of a succession of mixed populations of bacteria, actinomycetes and fungi associated with a diverse succession of environments, one overlapping the other and each emerging gradually as a result of continual changes in temperature and substrate. The principal environmental factors important in composting are moisture, temperature, pH, nutrient concentration and availability, and oxygen concentration.

Moisture

The minimum moisture content at which bacterial activity takes place is from 12 to 15 percent. The moisture content of composting material should be maintained in the range of 45 to 50 percent. Most sludge composting experience has been with sludge solids concentrations of 10 to 35 percent.

A recent paper by Haug and Haug[12] discusses the engineering and thermodynamic principles of composting systems and concludes in part that:

> Probably the single most important variable in determining the successful composting of sludge is the solids content produced during dewatering. Moisture and volatile solids control, and the energy budget for the system are largely influenced by this parameter. Implementation of any composting system should be coupled with serious consideration for maximizing dewatered cake solids. This conclusion is valid regardless of the type of composting system, whether windrow, aerated pile, or mechanical.

Temperature

Modern composting processes are designed to operate within the mesophilic and thermophilic ranges. The range of optimum temperatures for the composting process as a whole is quite broad, probably from about 35° C to 65° C. The temperature of a reasonably large composting mass will gradually rise to within the thermophilic range due to excess energy from microbial activity. This increase will inevitably take place unless positive measures are taken to dissipate the heat or improper composting procedures are used.

Sludge composting should reach thermophilic temperatures for a significant period of time for several reasons: (1) the optimum temperature for some of the organisms involved in the composting process is within the thermophilic range, (2) most pathogenic organisms and weed seeds cannot survive long exposure to thermophilic temperatures, and (3) a composting mass will reach thermophilic temperatures unless definite countermeasures are taken to dissipate heat.

pH

In practical operations little can be or needs to be done to alter the pH in a composting mass.

Nutrients

One of the more important nutrient requirements in composting is the carbon-nitrogen balance or ratio (C/N ratio). Part of the carbon is lost as CO_2 and carbon is present in the cellular material in greater concentration than is nitrogen; therefore, the amount of carbon required is considerably greater than nitrogen. The optimum C/N ratio for most wastes falls within the 20 to 25 parts carbon to 1 part nitrogen range.

The more the carbon-nitrogen balance deviates from the optimum, especially in the upper range, the slower the process proceeds. However, the actual upper limit for an individual application depends upon the degree of availability of the carbon. The principal deleterious effect of too low a C/N ratio is the loss of nitrogen through the production of ammonia and its subsequent volatilization. Apparently, any excess nitrogen ends up as ammonia. As far as the composting process itself is concerned excess nitrogen is not detrimental. Nutrient concentrations and balances in most sludges are adequate and not limiting to the composting process.

Oxygen

Optimum oxygen levels in a composting mass are believed to be between about 5 and 15 percent. Some method must be employed to achieve these levels in any aerobic composting method. Since the composting process is aerobic, low oxygen levels will slow down the process and may precipitate anaerobic conditions in some parts of the composting mass. Excessively high oxygen concentrations increase aeration expense and may reduce temperature.

Windrow Composting

The windrow process is conducted in uncovered areas and relies on natural ventilation plus periodic turning to maintain aerobic conditions. The sludge-bulking agent mixture is spread in windrows with a triangular cross section normally 6 to 15 feet (1.8 to 4.6 m) wide and 3 to 5 feet (0.9 to 1.5 m) high. An alternative method to mixing the bulking agent and sludge before forming the windrow is placing the bulking agent as a base for the windrow. The sludge is then dumped on top of the bulking agent and spread. A composting machine (similar to a large rototiller) then mixes the sludge and bulking agent and forms the mixture into a windrow. Several turnings (about 8 to 10 times) are necessary to adequately blend the two materials.

The windrow is normally turned at least once per day, with a composting machine, for a three week period, or longer depending on the weather and efficiency of composting. During rainy periods, turning is suspended until the windrow surface layers dry.

In the initial studies by the USDA at Beltsville, Md., digested sludge was successfully composted in windrows.[5,7] Fifty tons (45 Mg) of wet sludge (23 percent solids) were composted daily. The windrow process was found to be unsatisfactory for composting undigested primary and waste activated sludges because offensive odors were produced. Also, survival of coliforms and salmonella was extensive, with indications of regrowth, as material in the center of the compost windrows was shifted to the exterior when the windrows were turned. The unsatisfactory performance of the windrow process for composting undigested sludges led USDA researchers Epstein, Willson and their coworkers to develop a forced aeration, static pile method.[6,7]

The County Sanitation Districts of Los Angeles are currently composting an anaerobically digested and centrifuged primary sludge in the windrow process. Previously composted sludge is mixed with dewatered sludge in a 1:3 ratio, formed into windrows and composted for 21 days or longer. Mixing, forming, and turning the windrows are accomplished with mobile equipment. Approximately 100 dry tons (91 Mg) per day of 35 percent solids cake from solid bowl centrifuges were composted during a five year period beginning in 1972. Finished compost with a moisture content of approximately 40 percent is sold to Kellogg Supply Co. Kellogg hauls the compost to its nearby plant for further processing and packaging and pays for the compost on a royalty basis. The composted sewage sludge is blended with other ingredients to form various specialized soil conditioners. The basic product is marketed under the trade name Nitrohumus. Kellogg has developed several garden soil conditioning and fertilizer products as well as offering soil testing and analysis services. These products and services are marketed within a radius of about 300 miles (482 km) directly to large users, such as golf courses, commercial nurseries, and stadiums, and through retail outlets such as nurseries, garden stores and chain stores.

Studies were conducted by the Los Angeles County Sanitation Districts on the effects of windrow turning frequency on temperature, moisture content, volative solids content and survival of microorganisms.[13] Windrow turning frequencies ranged from three turns per day to one turn every three days. Turning was accomplished by passage of a Cobey Rotoshredder lengthwise through the windrows. Samples were collected from various points in the piles and tested including analyses for human parasitic worms, bacteria and virus. Conclusions from these studies include the following:

1. Temperatures as high as 60 to 65°C were achieved during compost cycles when rain did not occur and when the composting apparatus was consistently available throughout the cycle. It was concluded that more frequent turning produced temperatures above 60°C for longer periods of time. Ambient temperature, rainfall, and composter malfunctions caused temperatures in the interior of the compost windrows to reach only 55 to 60°C during winter months.
2. Human parasitic ova were monitored and intact ova of *Ascaris lumbricoides, Trichuris trichiura,* and hookworm were isolated throughout the compost

cycle. However, viability testing of these ova indicated that viable parasites are consistently present only through the first week and a half of composting. Viable *Ascaris* ova were isolated in only three of the final compost samples collected during this study. Six of 116 samples collected after more than one and a half weeks of composting contained embryonated *Ascaris*.

3. Total coliform and salmonella concentrations were rapidly reduced within the first week and a half of composting. Final compost coliform concentrations of less than one MPN per gram were obtained during warm weather composting in samples collected in the interior of compost windrows. Exterior windrow samples were not below one MPN per gram with consistency. Final compost salmonella concentrations of <0.2 MPN per gram were obtained in both interior and exterior samples collected from warm weather compost cycles. Regrowth of salmonella during winter compost cycles was observed, but it was not determined whether poor winter performance was due mainly to climate or failure of the composter.
4. Reduction of human pathogen concentrations to below the level of detection was achieved with greater frequency than achievement of the coliform standard of less than one MPN per gram dry weight. Assays of virus, parasitic ova, and salmonella yielded negative results in the vast majority of final compost samples; whereas total coliform concentrations in final compost samples were not uniformly below one MPN per gram.

In early 1977 the Los Angeles County Sanitation Districts installed second stage basket-type centrifuges that treat the centrate from the first stage solid bowl centrifuges. This method of operation increased the total sludge produced from about 100 dry tons (91 Mg) per day to about 275 dry tons (249 Mg) per day and increased the moisture content from an average of about 65 percent to about 80 percent. This increased moisture content has created odor problems in the windrow composting process while there had been no odor problem with composting the drier sludge. The Sanitation Districts and LA/OMA are investigating odor prevention procedures and alternative methods of composting such as forced aeration and the use of bulking agents other than composted sludge.

Forced Aeration Static Pile Composting

In the forced aeration static pile process the pile remains fixed, as opposed to the constant turning of the windrow, and a forced ventilation system maintains aerobic conditions. The static pile system developed by USDA for composting undigested sludge is illustrated in figure 8–2. The forced aeration system is in routine operation at Beltsville, Md., Bangor, Maine, and Durham, N.H. A system is under design for Camden, N.J. and pilot test work is in progress by LA/OMA at the Los

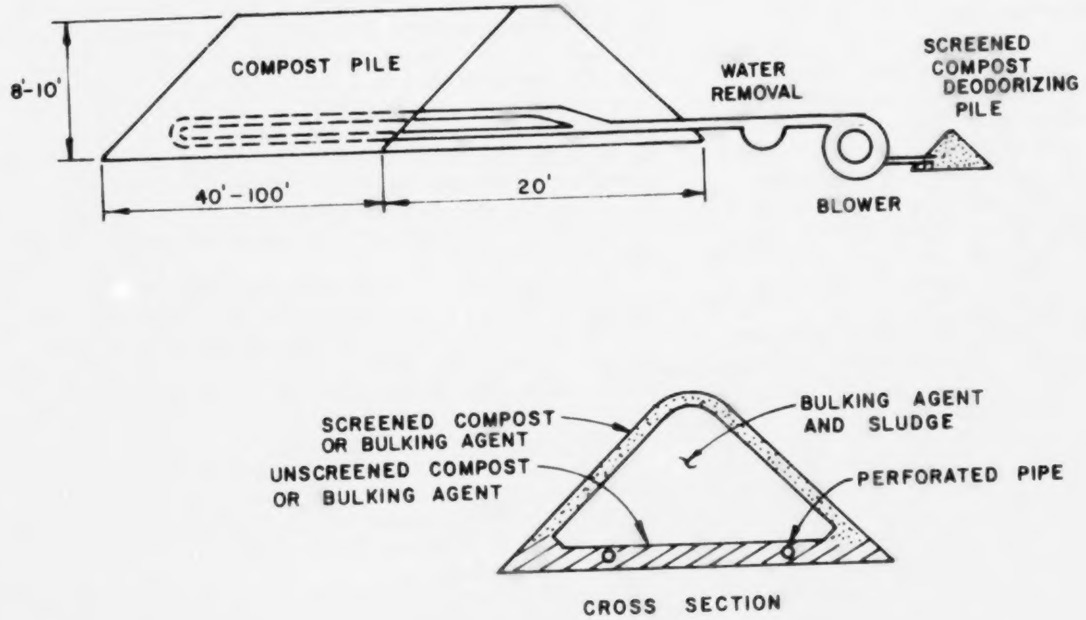

COMPOST PILE
8'-10'
40'-100'
20'
WATER REMOVAL
BLOWER
SCREENED COMPOST DEODORIZING PILE
SCREENED COMPOST OR BULKING AGENT
UNSCREENED COMPOST OR BULKING AGENT
BULKING AGENT AND SLUDGE
PERFORATED PIPE
CROSS SECTION

Figure 8–2.—Forced aeration static pile composting. Developed by the U.S. Department of Agriculture, Beltsville, Md.

Angeles County Sanitiation Districts plant in Carson, Calif.

Beltsville, Md.

Operations at Beltsville are described in several reports and articles.[5–7,14,15] This program is supported by EPA and operated jointly by the Maryland Environmental Service and USDA. Most of the Beltsville compost is provided free of charge to public agencies and it must be picked up at the site. As of January 1978 the Maryland State Department of Public Health will permit the use of this compost by individuals; however, the demand exceeds the supply and very little has been used by individuals to date.

As previously described, digested sludge was successfully composted at Beltsville by the windrow process. Static pile composting studies at Beltsville have been conducted with: (1) combination of primary and secondary undigested sludges, (2) 75 percent undigested and 25 percent anaerobically digested sludge, and (3) anaerobically digested sludge. The results of these studies were reported by Epstein et al.[6] Data on pathogen removal was reported by Burge et al.[16] It was concluded that:

1. Either digested or undigested sludge can be composted in an aerated pile without releasing objectionable odors.
2. Destruction of total coliforms, fecal coliforms, salmonella and virus was much greater than windrow composting. Survival of microorganisms in the lower corner of the triangular shaped piles was believed to be a result of the lack of insulation, or compost depth, and resulting heat loss in this section.

Currently, 50 tons (45 Mg) per day, 5 days per week are composted by the aerated static pile process at Beltsville. Undigested sludge cake (approximately 23 percent solids) from the Washington, D.C., Blue Plains wastewater treatment plant is delivered to Beltsville in 10 wet ton (9 Mg) loads by conventional 3 axle dump trucks. Two trucks are used and each truck makes 3 trips per day. Delivery generally begins early in the morning and continues into early afternoon. Prior to the sludge delivery, pads of bulking agent are prepared in the mixing area. These pads are 9 to 10 feet (2.7 to 3.0 m) wide, 1 to 2 feet (0.3 to 0.6 m) deep and as long as required for the bulking agent to sludge ratio mix for one truck load of sludge.

The sludge trucks arrive on site, are weighed, and then the sludge is dumped onto the bulking agent pad. A front loader is used to spread the sludge evenly over the top of the bulking agent. A Terex composter then moves along one side of the sludge-bulking agent pad and then along the other side, mixing the materials toward the middle to form a partially mixed windrow of triangular cross section. A Roto-Shredder then passes through the windrow, turns around, and passes back through the windrow. This operation mixes the sludge and bulking agent to form a relatively homogeneous blend. The Terex composter and Roto-Shredder are both used because they are available at Beltsville. Satisfactory mixing can be accomplished using either machine alone. Mixing can also be accomplished using only the front loader, but is more time consuming to produce a good mix.

Beltsville has been using the extended pile forced aeration composting configuration. Material is added to the pile each day and aeration pipes are spaced about every 8 feet (2.4 m) on center. The composting pad for each day's sludge-bulking agent mixture is prepared by laying out the aeration piping on the asphalt composting pad and covering this pipe with a 12-inch (0.3 m) layer of wood chips using a front loader. The sludge-bulking agent mixture is then placed on the wood chip base using a front loader. The mixture is piled to a height of about 8 feet (2.4 m). The top and ends of the pile are then capped with an 18-inch (0.5 m) layer of unscreened compost or a 12-inch (0.3 m) layer of screened compost. At the end of each day's operation the side of the pile (which will be added to the next day) is covered with a thin layer of compost. A 1/3 horsepower (0.25 kW) blower rated at 335 cubic feet (9.49 m^3) per minute is connected to the piping. A 5 cubic yard (3.8 m^3) pile of screened compost is placed over the end of the blower discharge piping for deodorizing the discharged air. The blower pulls air through the composting pile and discharges to the deodorizing pile. The blower is generally operated on an on-off cycle controlled by a timer. Currently, blowers are operated 8 minutes on and 12 minutes off in 20 minute cycles.

Generally, compost is removed from the opposite end of the extended pile each day, or every other day, after 21 days of composting. This part of the pile is dismantled using a front loader and is moved to the curing pile. The aeration pipe is a light weight plastic considered expendable and therefore, is moved with the compost. The compost stays in the curing pile for at least 30 days, usually for a much longer period, awaiting screening or off site use. The unscreened compost can be stored for long periods depending on the needs of the particular operation and the screening and compost distribution operations.

Processing of the dewatered raw sludge cake and formation of the compost pile must be carried out on a regular basis consistent with raw sludge delivery. Raw sludge is mixed with bulking agent (wood chips purchased from local contractors and lumberyards) and processed into a compost pile promptly as it is received on site to avoid odors. Raw sludge is not stored on site. Should site conditions or weather shut down operations (there are practically no instances of this occurring at Beltsville) sludge would not be delivered but would be either stored at the Blue Plains plant or diverted to other disposal sites.

Screening is used to separate the wood chips from the compost so that: (1) a portion of the chips can be reused, (2) the final product has a finer particle size, and (3) the carbon-nitrogen ratio of the finished compost is decreased. Most screening is performed with a 5/8 inch (1.59 cm) mesh rotary drum screen. The drum is 7 feet (2.1 m) in diameter and about 14 feet (4.3 m) long. The tilt of the drum and the feed rate are adjustable. Screening can be scheduled independent of other operations because of unscreened compost storage availability. In practice, however, enough compost is screened to meet: (1) any onsite need, (2) the demand from users, and (3) to provide room in the unscreened storage area for current production. Compost is screened at all times when the temperature is above freezing and it is not raining. Peak hourly capability of the drum screen with fairly dry material is about 50 cubic yards (38.2 m^3). However, under actual conditions of startup, shutdown, cleanup, and typical breakdowns, the input drum screen capability is about 150 to 250 cubic yards (114.7 to 191.1 m^3) per day. The screen is mounted on wheels and can be moved with the front loader for cleanup.

Other site operations include regular cleanup of work areas, receipt and storage of bulking agent, loading and measurement of finished compost for users, and equipment maintenance.

The staff at Beltsville consists of 8 people: 2 administrative and 6 operating. This number is more than actually needed for normal operations. The additional personnel are used for special operations and to support the research demonstration program. The operating staff is highly trained. Each member is qualified on each piece of equipment and the staff is able to perform all preventative maintenance and much of the repair work. Personnel and equipment are available for the composting operation full time. A list of equipment is shown in table 8–2.

The approximate materials quantities used in the Beltsville operation are shown in table 8–3. These quantities are based on: (1) annual undigested sludge cake (approximately 23 percent solids) input of 15,000 wet tons (13,600 Mg), (2) ratio of 2.1:1 wood chip bulking agent to sludge cake by volume (this is the ratio now being used at Beltsville), and (3) 5/8 inch (1.59 cm) screening of all compost for wood chip recovery and recycle of 70 percent (the wood chip loss/attrition rate at Beltsville is currently about 20 to 25 percent).

Table 8–2.—Beltsville equipment

2	Terex rubber tired front loaders, 4.5 cu yd
2	dump trucks, 10 ton, 3 axle
2	flat bed trucks, 1.5 ton
2	pickups
2	rubber tired farm tractors, one with loader
1	rotary screen with power unit
1	Sweco screen, fixed (new)
1	mobile rotary screen, small (not used)
1	Terex composter
1	Imco Roto-Shreader
1	large conveyor with engine drive (not used)
1	Fixed Toledo truck scale
1	mobile office
1	storage building
1	lot small equipment and hand tools

Table 8–3.—Beltsville materials requirement for 15,000 wet ton annual sludge input

Limed raw sludge, wet tons	15,000
Solids, percent	23
cu yd	20,700
Density, lb/cu yd	1,450
dry tons	3,450
Extended pile construction	
Sludge, cu yd	20,700
Bulking agent	
mixing w/sludge, cu yd	51,750
pile base, cu yd	8,100
Pile cover	
screened compost, cu yd	12,000 (12 in. cover)
unscreened compost, cu yd	18,000 (18 in. cover)
Individual pile construction	
Sludge, cu yd	20,700
Bulking agent	
mixing w/sludge, cu yd	51,750
pile base, cu yd	17,000
Pile cover	
screened compost, cu yd	24,000 (12 in. cover)
unscreened compost, cu yd	36,000 (18 in. cover)

Output or production quantities are shown for both a 12-inch (0.3 m) screened compost pile cover and an 18-inch (0.5 m) unscreened pile cover in table 8–4. The unscreened compost production is based on 15 percent reduction in sludge volume during composting and curing. This example serves only to illustrate general concepts because the materials loss through composting and curing are estimated and have not been precisely documented at existing operations.

Bangor, Maine

Composting began at Bangor in August 1975 and operations are described in detail in two recent reports.[8,14] The city of Bangor, Maine, has a permanent year-round population of 38,900 residents of whom 32,000 are served by the sewage treatment plant. The 32,000 residents provide a flow of about 3 Mgal/d (0.13 m^3/s) to the plant. Commercial and industrial establishments produce an additional 1 Mgal/d (0.04 m^3/s) and 0.7 Mgal/d (0.03 m^3/s) respectively, for a base flow of about 4.7 Mgal/d (0.20 m^3/s). Infiltration and storm water runoff contribute an additional 2.3 Mgal/d (0.10 m^3/s), making the average total flow about 7 Mgal/d (0.31 m^3/s).

This flow receives primary treatment consisting of passage through bar screens, settling in primary sedimentation tanks, and prechlorination. Sludge is pumped from the primary sedimentation tanks through a hydrocyclone

Table 8–4.—Approximate materials output, Beltsville type operation

Case[a]	Net unscreened compost production, cu yd	Net screened compost production[b] cu yd	Bulking agent, cu yd		
			Total required	Recycled	Net used (new make-up)[b]
Extended pile with:					
Screened compost cover	82,260	39,170	59,850	43,100	16,750
Unscreened compost cover ...	87,660	35,210	59,850	52,450	7,400
Individual piles with:					
Screened compost cover	101,070	51,570	68,750	49,500	19,250
Unscreened compost cover ...	111,355	43,351	68,750	68,000	750

[a] Materials input shown in table 8–3.

[b] Does not reflect actual Beltsville operations because only a portion of the Beltsville compost is screened.

Assumptions

1. 15 percent reduction in sludge volume during composting and curing.
2. 10 percent of the bulking agent lost in composting and curing cycle.
3. 20 percent of the bulking agent lost in screening (passing through screen into finished compost).
4. 15,000 wet ton annual sludge input.

for grit removal. The sludge flows by gravity to two sludge thickeners and is then pumped to a conditioning tank where lime and a polymer are added. The pH of the conditioned sludge is 11 to 12 and is dewatered by vacuum filtration.

The treatment plant currently produces about 3,000 cubic yards (2290 m^3) or 2,500 tons (2270 Mg) per year of vacuum filtered sludge with an average solids content of 20 percent. The vacuum filters are operated about 70 times per year, producing 40 to 60 cubic yards (30.6 to 45.9 m^3) of sludge each time.

Undigested raw lime conditioned sludge cake (approximately 25 percent solids) is delivered from the treatment plant, in 5 to 7 cubic yard (3.9 to 5.4 m^3) containers by a single lift and carry type truck, to the composting site located at the Bangor International Airport approximately 3 miles (4.8 km) from the treatment plant. Generally, the raw sludge is dewatered, delivered, and composted once a week; on occasions twice a week. Usually the dewatering operation is started the day before so that all available sludge containers are filled the morning composting is to commence. Sludge hauling to the site begins early on the morning of composting. An operator and 4 cubic yard (3.1 m^3) front loader are at the site on the day of composting. As the containers of sludge are delivered to the site, they are dumped on a previously prepared bed of bulking agent in the mixing area, mixed with the front loader, and the compost pile is formed over a previously prepared base. Generally, one composting pile is constructed per week and typically consists of approximately 40 to 60 cubic yards (30.6 to 45.9 m^3) of raw digested sludge cake mixed in 1:3 ratio with about 120 to 180 cubic yards (91.7 to 137.6 m^3) of bulking agent. Approximately 6 to 8 trips must be made to the site to deliver the sludge cake. The mixing and pile construction requires about 10 hours.

Bark is currently used as a bulking agent. Most composting piles are mixed in a 3:1 ratio of bulking agent to sludge cake. The bark consists of a wide range of particle sizes from very fine to 18 inches (0.5 m) long. When the bark moisture content is less than 50 percent it is satisfactory for composting. Moisture is a problem during rainy weather because the bark is stored outside. During winter, there is little rain and the bark is quite satisfactory.

The base for the compost pile is prepared using 7 feet (2.1 m) lengths of perforated schedule 40 steel pipe jointed together by short pieces of plastic pipe. The city found that the short lengths of steel pipe can be removed from the pile without significant damage and reused many times. Longer pipes were used previously, but were easily bent when pulled from the pile. The city has been experimenting with many different pile configurations. Currently, no base material is used; the sludge-bulking agent mixture is placed directly on the pad and aeration pipes. The city has also satisfactorily used unscreened compost as the bulking agent in a number of piles. Unscreened compost has been used up to three cycles as bulking agent with good results which has dramatically reduced requirements for new bulking material. The city plans further tests using unscreened compost as bulking agent.

The compost piles are constructed as high as the front loader can reach and capped with 1 to 2 feet (0.3 to 0.6 m) of unscreened compost. The finished pile is 10 to 12 feet (3.0 to 3.7 m) high. The blower is then operated on an on-off cycle drawing air through the pile.

It was found that during cold weather all available heat must be conserved to bring the piles up to temperature. Reuse of unscreened compost provides a warm bulking agent. The interiors of the bark storage piles are also sources of warm materials for mixing. Generally, if the sludge-bulking agent mixture can be maintained at about 4°C the pile will perform much better than if the mixture falls below 4°C. Recycle of warm exhaust air from an older composting pile into the new pile is also helpful for the first few days. The exhaust air from an older composting pile is very wet and will cause high moisture levels in the new pile receiving the air if used for more than the first several days. The city has also purchased a heater to provide initial heat to the piles.

The piles are composted at least 21 days. Temperature and oxygen levels are monitored every 2 to 5 days during the composting cycle. The blower operating cycle is adjusted according to the performance of the pile. The aeration pipes, blowers, and moisture traps are checked for freezing during cold weather because of the large amount of moisture drawn through the aeration piping.

At the end of the composting cycle the pile is dismantled, usually at the time another pile is constructed. The material removed from the pile is either used as the bulking agent for the new pile or is transferred to curing.

Raw sludge is not stored at the compost site, but is stored at the plant. Generally, operations are scheduled so that sludge is dewatered and a compost pile constructed once a week. The exact day of pile construction is varied depending on weather conditions. The city has been able to compost nearly all of the sludge production simply by selecting a good day each week for compost pile construction.

A Lindig rotary drum screen is used to screen compost prior to distribution. The drum is presently fitted with a 1-inch (2.54 cm) mesh screen. City personnel are planning to construct a 5/8-inch (1.59 cm) screen assembly so that either size material can be produced. Tests performed at Bangor indicate that the screen is capable of handling about 20 to 25 cubic yards (15.3 to 19.1 m^3) (900 pounds per cubic yard (533 km/m^3)) of feed per hour under the best conditions. Compost is put in the screen with a front loader. One loader operator and a laborer are required during operation.

Currently, operations at Bangor are being performed by treatment plant personnel under the direction of the treatment plant superintendent. There are no full time composting personnel because of the cyclical nature of the operations. Approximately 11 hours per week are required at the site, primarily for loader operation. In addition, approximately 9 hours per week are required for a truck driver to deliver sludge to the site. Sampling and monitoring for temperature and oxygen content requires 10 hours per week not including the pathogen and heavy metals monitoring which is performed under contract by the University of Maine. The supervision and administration requirements are about 15 hours per week. Annual equipment and labor requirements are shown in table 8–5.

The equipment used for composting operations is shown in table 8–6. This equipment is provided by the city motor pool and is available for composting when needed.

The approximate materials quantities based on 1976 sludge volume for the Bangor operation are shown in table 8–7. These quantities are based on an annual sludge input of 3,000 cubic yards (2290 m^3) and a mix-

Table 8–5.—Estimated annual operations requirements, Bangor, Maine[a]

Operation	Labor hours	Equipment hours
Composting, labor	572	
front loader		468
Sludge hauling, labor	468	
truck		468
Monitoring, labor	520	
pickup		520
Administration, labor	780	
Screening (8,000 cu yd), labor	1,040	
screen		520
front loader		520
Maintenance, labor	100	

[a] This table is based on information provided by the city of Bangor personnel.

Table 8–6.—Bangor equipment

1 case W24B rubber tired front loader, 4 cu yd
1 rubber tired front loader, 1.5 cu yd
1 truck, sludge container hauling
1 mobile screen, Lindig
Small tools as required
Miscellaneous vehicles as needed from motor pool

Table 8–7.—Bangor materials requirements for 2,170 wet ton annual sludge input

Limed raw sludge, wet tons	2,170
solids, percent	23
cu yd	3,000
Density, lb/cu yd	1,450
dry tons	500
Static pile construction	
sludge, cu yd	3,000
bulking agent, cu yd	9,000
pile cover, cu yd	1,560

Table 8–8.—Approximate materials output, Bangor type operation

Case[a]	Net unscreened compost production, cu yd	Net screened compost production, cu yd	Bulking agent, cu yd		
			Total required	Recycled	Net used (new make-up)
New or recycled bulking agent used in pile construction	10,920	4,160	9,360	6,760	2,600
Unscreened compost from pile used as bulking agent for one cycle	6,240	3,198	4,680	3,042	1,638
Unscreened compost from pile used as bulking agent for two cycles	4,654	2,785	3,114	1,868	1,246

[a] Materials input shown in Table 8–7.

Assumptions
1. 15 percent reduction in sludge volume during composting and curing.
2. 10 percent of the bulking agent lost in each composting and curing cycle.
3. 20 percent of the bulking agent lost in screening (passing through screen into finished compost).
4. 2,170 wet ton annual sludge input.

Table 8–9.—Compost pile performance, Bangor, Maine, 1975–76

Pile number	Compost period	Days to peak temperature	Days above 55° C	Peak temperature, °C	Average temperature, °C	Average ambient temperature, °C	Average O_2 (percent)
1A	8/19– 9/10	4	8	67	58	15	17
2B	8/26– 9/15	7	14	83	60	15	17
3C	9/2 – 9/25	5	21	65	60	16	18
4A	9/10–10/2	8	17	67	62	15	17
5B	9/23–10/10	15	9	72	63	11	13
6C	10/2 –10/17	8	12	76	75	10	13
7A	10/8 –10/31	7	18	76	73	7	12
8B	10/15–10/31	13	10	67	62	7	12
9A	11/7 –12/4	11	18	62	58	3	12
10B	11/13–12/23	17	0	50	50	–5	12
11C	12/3 –12/23	20	1	61	61	–11	9
12A	12/10–12/23	14	3	60	60	–12	14
13B	1/13– 2/5	20	15	66	60	–5	15
14C	1/15– 2/5	11	10	58	58	–6	15
15A	2/12– 3/8	20	7	60	58	–2	14
16B	2/23– 3/12	20	9	74	71	–5	11
17C	3/1 – 3/29	15	17	71	68	0	10
18A	3/9 – 3/30	17	10	70	68	5	10

ture of 3 parts bulking agent to one part sludge. The calculated materials production is shown in table 8–8 for three assumed cases. These production outputs assume a 15 percent reduction in sludge volume during composting and curing and one inch screening of compost before distribution. Recovery of bark is estimated at 70 percent by either screening and/or recycle of the unscreened compost as bulking agent.

Performance data are summarized in table 8–9 for 18 piles which were composted during 1975–76. The moisture content of the bulking agent varied widely from 40 to over 60 percent. Bulking agent used in piles 10B, 11C, and 12A was wet, very fine, and somewhat decomposed. Bulking agent of more uniform and larger size would probably have produced more consistent results.

Durham, N.H.

The city operates a primary treatment plant and produces approximately 15 cubic yards per week of raw dewatered (15 percent solids) primary sludge. The plant is to be expanded to secondary treatment and sufficient land is not available for the projected requirements for sludge spreading. As a result, the city set up a test program for evaluating aerated static pile composting and obtained a grant through the New Hampshire Department of Public Health. The purpose of the test was to determine: (1) whether proper composting could be accomplished outdoors in a severe northern climate and (2) composting costs.

Approximately 15 cubic yards (11.5 m^3) per week of raw primary sludge was composted on a temporary 1.75 acre (0.71 ha) site. Operations were conducted similar to those at Beltsville except air was drawn from the piles for 12 days and then blown into the piles for the rest of the period. It was found that temperatures would drop after 12 days if the air flow were not reversed. Wood chips were used as a bulking agent. Sludge-bulking agent mixing was accomplished with a combination of a front loader and motor grader.

The test operation was considered successful and the treatment plant and composting operation will be upgraded and expanded. This expansion will include a mechanized aerated static pile composting operation which will incorporate a number of materials handling features. Much of the materials handling will be accomplished with fixed equipment as opposed to the mobile equipment used previously. General operations will include the following:

1. Mechanized movement of sludge and bulking agent and measuring of the components to a specified ratio.
2. Mechanized mixing of sludge and bulking agent with fixed equipment to obtain adequate and consistent results independent of weather.
3. Mechanical movement of the mixture to the designated composting area and rapid construction of the pile.
4. Mechanical screening of compost and direct placement in curing bins (five months storage in year 2025).
5. A front loader will be used to form the piles, dismantle the piles, load the compost into the screen, transfer bulking agent from the storage bin to the mixer feed hopper and transfer finished compost from the curing bins to trucks.

The new Durham facility will be designed for producing approximately 10 cubic yards (7.6 m^3) of compost per day initially and 17 cubic yards (13.0 m^3) by 2025. The area required for composting is 15,000 square feet (1394 m^2), but with all appurtenant requirements such as sludge processing building, storage areas, roadways, and truck washing areas the total requirement is 3.5 acres (1.4 ha). The total estimated construction cost for the facility is $658,000 not including land and sludge dewatering equipment.

It is anticipated that the dewatering and composting facility will be staffed by 2 persons based on an 8 hour shift. For 2 or 3 days a week, these people will operate the facility with 5 hours a day for operations and the other 3 hours for clean-up, start-up and shutdown. The remaining days will be devoted to clean-up, maintenance and compost screening and testing. The work force will increase to an anticipated 6 persons in the year 2025 for the dewatering and composting operation.

LA/OMA

The LA/OMA project is supported by the city of Los Angeles, Los Angeles County Sanitation Districts, Orange County Sanitation Districts, State of California and the Environmental Protection Agency. The LA/OMA staff, its consultants and the member agencies are conducting comprehensive management studies for the approximately 900 dry tons (816 Mg) per day of sludge produced in the Los Angeles metropolitan area. Included in these studies are pilot tests and demonstration projects for various sludge treatment methods.

Forced aeration static pile composting is one process currently being tested. The test systems include two 10 × 10 × 10 feet (3.1 × 3.1 × 3.1 m) insulated concrete bins and several Beltsville type piles. Various bulking agents and operating modes are being studied in the concrete bins. Composted sludge, redwood chips and rice hulls in various proportions are being tested in the Beltsville type piles.

Mechanical Composting Systems

The early composting tests by Eimco were conducted with a mechanical composting unit.[4] The paper by Wiles[3] briefly describes several types of mechanical composting units in use throughout the world. Most of these units compost refuse and none are in service composting sewage sludge in the United States. The following sections briefly describe three mechanical systems that have some experience in processing sludge and may be useful in some applications in the United States. No attempt has been made in this paper to describe all mechanical systems available. The description of the following three systems is intended to provide general information on the types of available systems and does not imply that other systems are inferior or that those systems described herein are preferable to other systems.

Fairfield Digester System

The Fairfield Engineering Co.
Marion, Ohio
(614) 387-3327

The Fairfield Digester is a circular vessel. Aerator augers are suspended from a bridge that travels around the top of the digester wall. Integral units of the bridge include: (1) drive machinery to rotate the bridge, (2) machinery for the multiple aerator augers, and (3) a conveyor which transports incoming material from an overhead center hopper to the place where it enters the digester near the wall. The material is aerated and moved toward the center discharge by the action of the multiple augers. A conveyor at the bottom of the digester removes digested material. Air is forced into the digester by a motor driven blower and distributed throughout the material by pipes.

Self-generated temperature of approximately 150 degrees Fahrenheit is produced and maintained by the metabolism of the aerobic-thermophilic microorganisms multiplying within the waste material. No starter inoculants or external heat are used. The speed of the augers, the rate of rotation of the carriage assembly and the amount of air introduced into the digester are controllable to obtain optimum temperature and correct retention time of material in the digester. Sensors provide the means for automatic control. They measure conditions at a number of locations within the digester and provide automatic adjustment of controls which maintain desired operating conditions.

From May 27, 1969, through July 7, 1969, the Fairfield Digester at Altoona, Pa., which normally is utilized commercially for processing garbage collected from the city of Altoona, was used to process 459 tons (416 Mg) of vacuum filtered raw sludge cake (75 percent moisture) from the primary clarifiers of the sewage treatment plant.[17] The volume of the sludge cake was reduced approximately 65 percent during a seven-day processing cycle.

The Fairfield Digester at Altoona is 38 feet (11.6 m) in diameter and, with a depth of material of 6 feet (1.8 m), has a capacity of 25 tons (23 Mg) per day organic input containing 58 percent moisture and weighing 30 pounds per cubic foot (480 kg/m^3). The digester is totally enclosed with air pipes in the bottom which receive forced air from the plenum chamber by means of motor valves that are operated automatically from temperature and oxygen probes located in the bottom of the digester. The digester is of continuous flow type so that digested material, having been retained in the digester approximately 7 days, is automatically discharged as new material is introduced. The sludge cake with conditioner is conveyed across the top of the digester and introduced adjacent to the wall. Multiple augers, supported from the enclosed top of the digester, aerates the material up and down and at the same time moves the material toward the center discharge port. The top deck turns 360 degrees and the augers revolve at different speeds.

The digester was emptied and the test was started by mixing approximately 2 tons (1.8 Mg) of shredded paper with 18.5 tons (17 Mg) of sewage sludge cake containing 75 percent moisture. A mechanical shredder was utilized to properly size the sludge cake and more effectively mix the paper with the sludge before the mixture was conveyed to the digester. This same approximate mixture of sewage sludge and paper was introduced into the digester 5 days per week, until the material reached a level of 4 feet (1.2 m) which automatically started to discharge digested material. This digested material, containing approximately 50 percent moisture, was then dried, to approximately 10 percent moisture, in a rotary dryer and recirculated back through the digester as a conditioner for the sludge cake.

For mechanical reasons, the density of the material within the Altoona digester must be kept below approximately 30 pounds per cubic foot (480 kg/m^3), so, after several days of using dried recirculated digester output as the conditioning material, it was found necessary to add a small amount of paper to the mixture. Thereafter, each day until the test was terminated, 0.25 ton (0.23 Mg) of paper and 5.36 tons (4.86 Mg) of dried digester output were mixed with 14.5 tons (13.2 Mg) of sludge cake having 75 percent moisture.

The digester input material weighed an average of 25 pounds per cubic foot (400 kg/m^3) and had pH of 5.6. The material discharged from the digester weighed 30 pounds per cubic foot (480 kg/m^3) and pH was 7.5. During the tests, the sludge cake was reduced by approximately 80 percent in total weight, 33 percent in solids weight, 98 percent in water weight, 50 percent in organic matter weight, and 65 percent in volume.

Metro-Waste

Resource Conversion Systems, Inc.
9039 Katy Freeway
Houston, Tex. 77024
(713) 461–9228

Resource Conversion Systems, Inc., offers the patented Metro-Waste Aerobic Thermophilic Bio-Reactor and associated equipment for application in the composting of wastewater sludge. The Bio-Reactor consists of systematized mixing, conveying, agitation, aeration and finishing. The Bio-Reactor system is fully automated, has continuous process control and monitoring equipment, and is enclosed for all weather operation. The process utilizes a bulking agent to assist in the handling and aeration of the dewatered residuals in the thermophilic aerobic Bio-Reactor. The bulking agent and dewatered residuals are blended together in a matrix mixer and then transferred via conveyor into the aerated Bio-Reactor. The Bio-Reactor consists of a patented agitation and aeration system. The stabilized residuals are then transferred via a conveyor to a bulking agent recovery and recycle system and then to an interim storage facility. Moisture content of the residuals is reduced from 75 to 85 percent to about 30 percent.

The company offers either a complete equipment system or individual components for dewatering and aerobically composting municipal and industrial organic wastewater residuals.

BAV System

Biowaste Management
175 East Shore Road
Great Neck, NY 11023
(516) 482–5944

There are over 30 of these systems operating on sewage sludge in Germany, France, and Japan. In these operations, sludge with a water content of about 98 percent, is concentrated by centrifuging or pressing to achieve about 75 to 80 percent water. Initially, peat, sawdust, chopped straw, brown coal, or some other acceptable carbon carrier is mixed with the sludge. The mixed material passes through the bioreactor from top to bottom in about 2 weeks. Air is forced in at the base of the bioreactor and passes through the material from bottom to top. Samples and temperatures from different levels are monitored continuously. The bioreactor attempts to provide optimum conditions for micro-organisms to multiply rapidly, and efficiently cause decomposition of the material into compost.

COMPOSTING COSTS

Sludge composting may be a viable alternative for many locations but the basic processes are still in the development and demonstration phase. Consequently, it is not possible to prepare generalized cost estimates at this time. Some cost considerations and estimates prepared in several studies are presented.

The cost of sludge disposal by composting may be considered in two components: (1) capital, operation and maintenance costs of producing the compost, and (2) cost of (or income from) disposal of the compost product. A market study[18,19] found several successful municipal sludge composting operations where all of the end product was sold or otherwise successfully used. The study concluded that the current upper price limit for bulk sludge compost is about $4 to $10 per ton ($4.41 to $11.02/Mg) and for packaged, bagged, sludge compost, about $60 per ton ($66.14/Mg). Bagging costs could approach $30 per ton ($33.07/Mg). Sludge compost marketing operations that have been successful have generally: (1) had favorable local publicity, (2) had the product available for pickup (or made deliveries), (3) offered guidelines for its use, or at least suggestions, (4) offered the product at no or low cost, and (5) given the product a trade name.

A study of the sludge disposal alternatives for the New York–New Jersey metropolitan area developed a cost of $40 to $45 per dry ton ($44.09 to $49.60/Mg) for composting large quantities of dewatered sludge without any hauling or land costs included.[20] A study by USDA estimates total costs for composting in 10 and 50 dry ton (9 and 45 Mg) per day facilities to be $51 and $36 per dry ton ($56.22 and $39.68/Mg), respectively.[21] A report by Camp, Dresser and McKee estimated a cost of $45 per dry ton including land, but excluding hauling, to windrow compost 600 wet tons (544 Mg) per day of sludge.[22]

Composting costs are documented for both Beltsville and Bangor.[14] The Beltsville costs must be considered carefully because they include allowances for various research activities and the equipment and site may be capable of handling two to three times more sludge than is presently processed. Various financial aspects of the Beltsville operations are shown in table 8–10. The 1976 actual and projected 1977–78 costs were developed

Table 8–10.—Beltsville actual and projected costs

	Projected Oct. 1977–Sept. 1978	Actual 1976	Estimated costs[a]	
			18,200 wet tons/yr[b]	45,500 wet tons/yr
Onsite operations				
Telephone and travel	$1,300	$3,971	$1,300	$1,300
Utilities	2,211	426	2,211	3,000
Fuel and oil	10,500	13,036	10,500	25,000
Sludge hauling	132,000	120,000	—	—
Labor including fringes	125,750	152,919	80,000	125,750
Miscellaneous contract services	27,540	[c]112,942	27,540	37,000
Wood chips	144,000	73,145	[b]144,000	[b]350,000
Supplies and materials	22,250	32,176	22,250	35,000
Equipment insurance	4,000	3,955	4,000	4,000
Total excluding offsite	469,551	512,570	291,801	581,050
Dry tons sludge per year (23 percent solids)	3,450	3,450	4,200	10,500
Annual cost, $/dry ton sludge solids	$136	$149	$69	$55

[a] Excluding requirements of research work.

[b] Assume 50 percent of compost marketed unscreened and 70 percent recovery of bulking agent after screening finished compost.

[c] Includes screening performed by outside contract, screening now performed on site by MES personnel.

from information on the total operation including research, but do not include the amortization of equipment or site costs. The onsite labor cost includes site supervision. Sludge hauling cost is for contract transport of sludge cake from the Blue Plains Plant to the composting site and are site specific for the Beltsville operation. Costs for bulking agent may not reflect actual usage because chips are purchased when prices are favorable and large quantities can be stockpiled. Screening in 1976 was performed by outside contract, however, all screening is now performed using onsite labor.

The projected Beltsville costs for 1977–78 were modified to show two different sludge input rates and research related costs were removed. Individual breakdown of costs for various processes such as mixing, pile construction, and screening are not available from Beltsville. However, cost estimates were prepared for an operation similar to Beltsville based on time and motion study at Beltsville. This study estimated that total costs, including capital amortization, are approximately $51 per dry ton ($56.22/Mg) of sludge cake solids for an operation processing 10 dry tons (9 Mg) of sludge solids per day. Total capital costs for site improvement and equipment were estimated at $376,000. Estimated costs for 50 dry tons (45 Mg) of sludge solids per year were $36 per dry ton ($39.68/Mg), including amortization of approximately $1,500,000 of capital costs. Costs from actual operations indicate that these estimated costs may be on the low side.

The following costs are for operations at Bangor, Maine, during 1975–76.

	Costs to compost 525 dry tons per year ($/ton)
Capital amortization, 6 percent, 5 years	3
Operations	43
Bulking agent	37
Analysis	8
Total	86

The capital investment was very low because only minor site work was required. Equipment is provided by the City Motor Pool. Amortization of equipment is included in the hourly equipment charge under "Operations." Cost information is not available for 1976. An estimated breakdown of labor and equipment by operation is shown in table 8–5.

Preliminary estimates at Durham, N. H., indicate a cost of about $107 per dry ton ($117.95/Mg) solids for 20 percent solids sludge[5] for composting an estimated 200 to 250 dry tons (181 to 227 Mg) of sludge per year excluding capital amortization.

The major cost items at existing composting operations are labor and bulking agent which can each be 30 to 45 percent of the total annual cost. Operation and maintenance of the mobile equipment at Beltsville, excluding capital amortization, is 10 percent or less of the total annual cost. Amortization of the purchase cost of the equipment at Beltsville (approximately $400,000) over 6 years at 7 percent would be approximately $84,000 per year or about 13 to 23 percent of total annual costs shown in table 8–10.

SOME EUROPEAN COMPOSTING SYSTEMS

The major interest in composting in Europe is directed toward the treatment of municipal solid waste. Much attention has been paid to methods for reducing the size of the waste and sorting out noncompostable materials. Sludge is accepted in most systems as a source of moisture and nitrogen to help reach a desirable C/N ratio. Night soil and disposable plastic latrine containers, both of which are essentially equivalent to raw sludge, are also composted in some systems.

In Sweden a recent law offers subsidies to communities to compost solid waste, and the process is seen as a good way to get rid of some of the increasing volumes of sludge that are being generated as Sweden approaches 100 percent secondary treatment of sewage. In November 1977 a compost conference and trade show in Jonkoping, Sweden, attracted 500 visitors, 300 of whom represented community officers. Six companies described their composting systems, some of which are currently under construction in Sweden. The Swedish National Nature Protection Agency operates a composting research plant at Laxa which has been described.[23] Current operation of the plant and experience with the equipment was described in a paper in Swedish by Mr. Hovsenius.

Although most of the descriptions were directed toward the composting of solid waste, any of the systems can be used to compost sludge if it is mixed with a suitable filler to allow air penetration. Bark, wood chips from tree trimming and old compost have all been used for this purpose. Any of the companies represented at the meeting would be happy to design composting equipment specifically for sludge. Many of the companies in fact offer several combinations of equipment to suit their customer's needs. Therefore, naming the manufacturer does not necessarily identify a particular process.

About half of the composting equipment described in the trade show is for size reduction. Essentially any chopping or grinding mill that can reduce solid waste to less than 4 inch (100 mm) pieces can be used to prepare material for composting. Chopped waste from which metals, glass and plastics have been removed is an effective filler for sludge composting, although in general the emphasis has been reversed and sludge has been considered as an adjuvant to the composting of solid waste. Where chopped bark is used as a filler for sludge composting, the high price of bark is cited as a major disadvantage. Although Sweden is rich in forests, bark commands a price equivalent to its fuel value in heating oil. On the other side, the acceptability of compost made from solid waste is less than that made from sludge alone because obvious traces of glass, aluminum, plastics and rubber remain from the solid waste.

In Europe, the emphasis seems to be turning from ingenious mechanical reactors and solids handling devices to systems for more efficient operation of classical windrow composting. Gunnar Hovsenius reported that the two mechanical reactors that have been studied at Laxa are now out of operation because forced aeration in windrows is more attractive. Even with the most advanced automatic composting reactor the product is removed after the heating stage and stored in piles to cure for periods of several weeks to months.

Composting Reactors

The original DANO company is bankrupt but licenses to build DANO type drum reactors are offered by a Swiss holding company, DANO Ltd., CH-Glarus. A DANO composter is a long rotating drum that looks like a cement or lime kiln. Typical dimensions are 11 ft (3.5 m) diameter and 90 ft (28 m) long. The drum rotates at 0.6 to 2 rpm tumbling the contents against specially designed baffles. Air is drawn through the drum countercurrent to the flow of composting material and discharged to an odor trap. Unchopped solid waste and sludge or water to provide moisture are charged to the inlet of the drum. With a retention time of 48 hours the temperature will reach approximately 140°F (60°C). Moisture and the elevated temperature weaken paper and packaging materials, and the tumbling action provides good disintegration of municipal wastes. The elevated temperature also kills pathogenic microorganisms and plant seeds.

Dano reactors are sometimes operated with as little as 24 hours' retention time. Although this is sufficient for disintegration of solid waste, the contents do not reach disinfecting temperatures, and some seeds may survive. The output from a DANO reactor may be screened through 3/4 inch (20 mm) holes with about 50 percent recovery based on the initial charge of solid waste. Further screening through 3/8 inch holes (10 mm) gives a 25–30 percent yield of fine compost. Wastes may be chopped before charging to the reactor and sludge may be composted with bark or chopped branches instead of municipal garbage. Operating characteristics of a DANO composter were quoted as follows:

	Weight		*Volume*	
	Metric tonnes	*Tons*	*m^3*	*Cubic yards*
Daily capacity	130	143	630	824
Municipal waste	100	110	600	785
Sewage sludge	30	33	30	40
Yield of finished compost	50	55	70	92
Compressed rejects	38	42	46	60

Dano composters were quoted as costing from 15 to 30 million Swedish kroner equivalent to $4 to $8 million depending on the peripheral equipment.

The "System Kneer" is offered in Sweden by BIAV, S-11288 Stockholm. This is a squat silolike reactor up to 60 ft (18 m) in diameter and 45 ft (13.5 m) high. Raw wastes are chopped, mixed and charged to the top of the reactor and finished compost is withdrawn from the bottom by a special helical screw. This helix rotates axially conveying compost to a central discharge port while at the same time it revolves around a central pivot like the hand of a clock to bring waste from all sectors of the reactor. Air is warmed by passage through a heat exchanger and injected at the bottom. Warm moist air is withdrawn from the top and passed through the heat exchanger preheating the incoming air before being discharged to an odor trap. Temperatures in the reactor approach 176°F (80°C) after 48 hours and compost remains in the reactor for 8 to 14 days. The original "System Kneer" was designed to compost sludge mixed with bark, wood chips or an inert filler in the ratio of 1 part of sludge to 1–2 parts of filler. The first installation to use chopped solid waste in Sweden ran into difficulties when the waste set to a solid that blocked the discharge screw. The screw has been redesigned but remains a critical part of the system. A BIAV-Kneer reactor with a capacity of 30,000 ton per year was quoted at about 5 million Swedish kroner or $1.25 million.

The Carel-Fouche reactor tower installed at Laxa for composting solid waste plus sludge is not now in operation. The tower measures 10×13 ft (3×4 m) in cross section and is 40 ft (12 m) high. In this reactor, five successive stages of composting are held, one below another, on special "forks" with a forced updraft of air. After one to three days' detention the forks are successively rotated starting at the bottom so that each layer drops to the next lower fork and the finished compost is removed on a conveyor for curing. A somewhat similar reactor tower resembling a multiple hearth incinerator is shown in literature distributed by Hazemag.

The INKA Compost Plant made by Johnson Construction Co. AB, S-17124 Solna, Sweden, that was installed at Laxa has been dismantled and moved to Milan, Italy. In this system an overhead traveling bridge rides on the top of two walls about 8 ft (2.5 m) high and about the same distance apart. Solid waste mixed with sludge is piled between the walls and is agitated by means of two helical screws like post hole augers that introduce air through hollow central shafts. This aeration proved to be insufficient so forced aeration was introduced through a gravel bed under the compost. Experience with the INKA reactor led directly to the forced aeration studies in static windrows.

The SILODA System of ODA, Courbevoie, France, also holds compost between walls in what they call a silo. A special "Paddle Wheel" resembling the stern wheel of a river steamboat rides on the walls, cuts and lifts the compost and deposits it in the adjacent silo. Compost remains in the silos for 8 to 14 days during which time it is turned 4 to 5 times.

Forced Aeration Composting in Static Piles

There has been a marked swing away from mechanically turned composting in reactors to forced aeration in static piles. Major experimental work has been done by Gunnar Hovsenius at Laxa. Voest-Alpine, A-4010 Linz, Austria, has reported temperature profiles in forced aeration compost bins. Ruthner, A-1121 Vienna, Austria, treats wastes for a short time in a DANO type drum, then charges the compost to bins with forced air suction.

The Laxa forced aeration system places compost on paved slabs on which three inverted concrete "U" beams are laid nearly 7 feet (2 m) apart and held above the pavement by 3/8" (8 mm) rods. Chopped waste blended with sludge is piled on top of the "U" beams in flat topped windrows 7 to 10 ft high (2 to 3 m) and up to 30 ft (9 m) broad. Blowers are attached to the concrete channel beams to provide either suction or forced air to the piles. There are specific difficulties associated with each of the modes of aeration but on the whole Laxa has had most luck with forced air moving up through the piles. It is possible that a combination of suction and blowing at different stages of composting will prove to be better than either mode alone.

In the winter months outside air temperatures at Laxa drop to zero°F (–18°C). The incoming air is bone dry but when it is blown through the pile, it becomes saturated with moisture at the pile temperature, which may exceed 160°F (71°C). When this moist air comes in contact with the cold outside air, most of the moisture condenses soaking the outer layer. At the same time compost near the air inlet channel is dried out. When air is sucked through the pile in winter, the outside layers are dried by the incoming cold air and composting activity in these layers stops. Moisture meanwhile condenses on the cold floor and ducts and must be removed before the air reaches the blowers. Disposal of the condensate is a problem since it is highly polluted and corrosive. Conceivably it could be sprayed on the piles to help maintain the desired moisture level. With either mode of operation moisture must be supplied to the pile when parts of it get too dry.

The composting process is an efficient method for drying sludge for the heat of biological oxidation. However, the initial moisture content must not be so high that it interferes with aeration. The maximum moisture level that can be tolerated depends on the structure of the supporting filler, whether it be fresh wood chips, bark, old compost or shredded solid waste. The most important criterion is that there be open spaces for air circulation throughout the pile to prevent the formation of anaerobic zones. Too high a pile may crush the filler and destroy air passages in the lower layers. The maximum proportion of sludge that can be tolerated must be determined by experiment for each site. The moisture content of the composting mixture is usually held below 60 percent and optimum values are usually quoted at 50 percent. If the sludge contains 80 percent moisture (20 percent solids) and the filler is dry then 53 parts of filler must be added to each 100 parts of sludge to achieve 60 percent moisture in the final mixture. More commonly the filler is moist and larger quantities are required. If the percent moisture of sludge, filler and initial compost mixture are S, F and C respectively, and M is the weight of filler per unit weight of wet sludge then

$$C = \frac{S + MF}{M + 1} \quad \text{and} \quad M = \frac{S - C}{C - F}$$

On the dry side, when moisture levels drop below about 40 percent, composting effectively stops. In one study at Laxa composting action stopped after 40 days of forced aeration when the reaction was only half completed. Additions of moisture restarted the reaction and allowed it to go to completion.

The air supply must be sufficient to provide oxygen and to dilute the CO_2 produced. According to Hovsenius the best control strategy is to keep the CO_2 content of the air leaving the pile between 3 and 6 percent by volume. He uses an infrared CO_2 meter for this purpose. When the CO_2 content exceeds 5 percent, the rate of reaction begins to fall and composting essentially stops when the CO_2 level reaches 10 percent. During the period of maximum activity the air demand is 2 to 3 times the volume of the pile per hour or about 1 to 1.5 cu ft of air per minute for each cubic yard of compost. Lower quantities of air must be used in later stages as the rate of composting declines to avoid drying out the pile.

The progress of composting can be measured by the CO_2 produced. In the Laxa studies using shredded solid waste and sludge the production of carbon dioxide leveled out when about 40 percent of the carbon in the waste had been converted to CO_2. The practical control remains temperature inside the pile which can be easily and rapidly measured with probe thermometers. When the temperature drops below 104°F (40°C), the pile can be moved to storage for final curing.

Odor Traps

Odor control is necessary in all systems in which air is passed through a composting mixture. Almost all of the systems use some sort of a biological filter as an odor trap. One DANO installation uses 16 inches (400 mm) asbestos cement pipes spaced 8 ft (2.25 m) apart. The pipes are perforated and covered with 1–2 inch (40–70 mm) gravel to a height of 16 inches (400 mm) above the tops of the pipe. A layer of fresh compost about 5 ft (1.5 m) high covers the gravel. There is sufficient moisture and organic matter in the exhaust gases to maintain an active deodorizing chemical microbial flora even on old compost or soil, but the use of fresh compost insures good deodorizing from the start. Another deodorizing technique is to blow the foul air directly into activated sludge or through a trickling filter if the compost plant is situated on the grounds of a sewage treatment plant. In every case provision must be made to remove condensed water and particulate matter that would corrode and clog blowers and air distribution systems.

Curing and Handling

All reactor systems, including forced aeration in static piles, provide separate areas for curing the fresh or immature compost. Curing is usually done in bins or in piles on paved storage areas. Storage areas may have to be covered and drained to comply with local requirements. Curing usually requires several months of storage.

Most of the systems use mobile equipment especially front end loaders to move and pile compost. A number of elaborate conveyor systems have been built to handle compost, but the large fixed investment and relatively small fraction of the time that the equipment is actually operated lead to very high unit costs. Mobile equipment is more versatile and although it requires more labor, it is apt to be cost effective for all but the very largest installations.

The Cost of Composting

It is not possible to translate costs of composting to U.S. equivalents without making corrections for the generally higher interest rates and lower labor costs in Europe. Costs of the order of $10 to $15 per ton ($11.02 to $16.53/Mg) of raw composting mixture were quoted at the Jonkoping meeting. The sales value of compost varies according to the market. A value of zero is realized when a plant uses composting to stabilize wastes, remove water from sludge and reduce the total volume for land filling. At the other extreme is fine compost that may be solid in bags for home garden use. Much of the compost that has been produced so far has gone to city parks and green areas and has not been sold on the open market. Some compost is used in truck gardens and there appears to be a good market for compost in the wine growing areas of central and southern Europe. Markets for recovered iron scrap and paper are quite undependable although profit from the sale of these items is frequently entered in the net cost of composting by promoters of equipment.

The yield of finished compost depends on the nature of the raw materials and the amount that is removed by screening. At Laxa with forced aeration one ton of mixed waste yields 1,060 lb (480 kg) of dry compost containing only 240 lb (109 kg) of organic matter. In the DANO literature one ton of mixed waste is expected to yield 770 lb (349 kg) of screened compost passing a 3/4 inch (20 mm) mesh.

DESIGN EXAMPLE

Engineered composting systems applied to the stabilization of sewage sludge are a relatively recent development in the United States. There appears to be general agreement among knowledgeable people in the field that the forced aeration static pile method, as developed at Beltsville, Md., could be used in many locations. One or more mechanical type systems may prove to be useful in some applications. The greater space required for the windrow system will restrict consideration of its use in many locations.

Sludge composting at Beltsville, Bangor, and Durham are all research and demonstration type operations. Many of the criteria required to design a system are not firmly established and there is certainly not a "typical" design at the present time. The LA/OMA project in California is currently conducting research in an effort to determine more design and operating criteria.

Composting is largely a materials handling process and to date the systems operating on sludge in the United States all utilize mobile equipment. Bulking agent and labor costs are the largest components in total sludge composting costs. There appear to be opportunities to significantly reduce composting costs if (1) more efficient methods of materials handling can be developed to reduce labor costs and space requirements, and (2) operating procedures can be developed to reduce, or eliminate, the amount of bulking agent required.

This design example is a 4 Mgal/d standard activated sludge plant and is based on a Beltsville type sludge composting system utilizing existing technology and available design criteria.

Sludge and Bulking Agent Characteristics

The following sludge quantities are used in the example.

	Pounds/million gallons			*Percent*
Sludge type	*Total solids*	*Volatile solids*	*Inerts*	*volatile solids*
Primary	1,300	780	520	60
Waste activated	1,000	800	200	80
Total	2,300	1,580	720	69

These sludge quantities were determined with the following assumptions:

1. Raw wastewater suspended solids = 240 mg/l; BOD = 200 mg/l.
2. Suspended solids removal = 65 percent in primary treatment and 90 percent overall; BOD removal = 30 percent in primary treatment and 90 percent overall.
3. One-half pound activated sludge produced per pound BOD removed.

It is further assumed that:

1. Primary sludge is 4 percent solids and is gravity thickened to 8 percent solids.
2. Waste activated sludge is 1 percent solids and is thickened to 4 percent solids.
3. Combined thickened primary and waste activated sludge (5.5 percent solids) is dewatered to produce 20 percent solids sludge per composting.

The weight and volume of sludge and bulking agent at various points in the process must be known to determine the configuration of a composting facility. The basic design decisions include: (1) the bulking agent to sludge ratio, and (2) the ratio of new to recycled bulking agent.

The materials flow system in this example of composting 2,300 pounds per million gallons (276 kg/1000 m^3) of 80 percent moisture undigested sludge is based on the following assumptions:

1. New and used wood chips are added to the wet sludge at the rate of 2.5 cubic yards (1.9 m^3) of chips per ton of wet sludge. This corresponds to a volume ratio of bulking agent to sludge of about 2.25:1.
2. Three-fourths of the chips will be recovered by screening and reused.

Information on the bulk density of sludge is surprisingly scarce in the literature. Tests conducted at Beltsville for an engineering study of a large scale composting facility provide some basic data on the bulk density of sludge and wood chip bulking agents.[24] The following bulk densities are used in this example:

	Bulk density (pounds per cubic yard)
Dewatered sludge (20% solids)	1,800
New wood chips	500
Recycled wood chips	700
Screened compost	865

Design Criteria

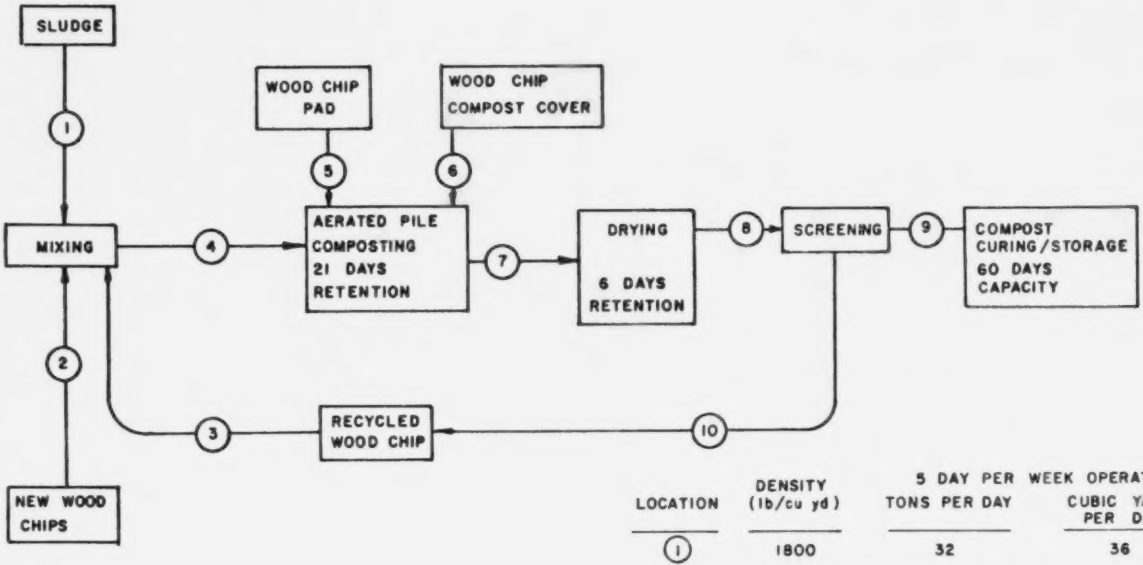
The following criteria are used in this example for a 4 Mgal/d (0.18 m^3/s) plant and are based on available operating experience.

1. Sludge composting system is operated 5 days per week, 8 hours per day.
2. Sludge to be composted
   - 46,000 wet pounds (20,870 kg) per day (80 percent moisture).
   - 26 cubic yards (19.9 m^3) per day (wet) = 182 cubic yards (139.1 m^3) per week.
3. Bulking agent required
   - 60 cubic yards (45.9 m^3) per day total.
   - 15 cubic yards (11.5 m^3) per day makeup (new material) = 105 cubic yards per week.
4. The composting area is to be sized for 21 day composting period.
5. The input volume of sludge and bulking agent to the composting pad is 31,025 cubic yards (23,720 m^3) per year or an average of about 120 cubic yards (91.7 m^3) per day based on a 5-day week.
6. Compost piles constructed in a triangular cross section, 8 feet (2.4 m) high with 16 feet (4.9 m) wide base. (Volume = 64 cubic feet per foot of pile length.)
7. Individual compost pads will be sized to hold two days sludge. Therefore, each pad will accommodate 240 cubic yards (183.5 m^3) of sludge-bulking agent mixture and will be 20 feet (61.0 m) wide and 100 feet (30.5 m) long.
8. Provide 15 percent excess composting area; therefore, 12 composting pads, each 20 × 100 feet (6.1 × 30.5 m) are required.
9. Provide one blower for each composting pad. Size blower for a minimum rate of 500 cubic feet per hour per ton (15.6 m^3/hr/Mg) of sludge solids. Use blower rated at 200 cubic feet per minute (5.7 m^3/min).
10. Provide 10 cubic yards (7.6 m^3) deodorizing pile to serve 2 blowers.
11. Provide leachate and condensate collection system for each pad with 50 gallons (0.19 m^3) per day capacity. Recycle leachate and condensate to treatment plant or sewer.
12. Composting produces finished screened compost with the following characteristics
    - 40 percent moisture.
    - volatile solids reduced 15 percent.
    - 25 percent of bulking agent remains in compost.
    - bulk density = 865 pounds per cubic yard (513 kg/m^3) (32 pounds per cubic foot).
13. Provide covered and paved area for 60 days storage (900 cubic yards (688 m^3)) of new wood chips. If bulking agent stored 8 feet (2.4 m) deep, then area required is about 3,000 square feet (279 m^2).
14. Finished screened compost production
    - 31,250 pounds (14,170 kg) per day.
    - 36 cubic yards (27.5 m^3) per day (13,140 cubic yards per year).
15. Composted moisture dried to 40 percent moisture before screening. Provide six days drying with material two feet deep; 10,000 square feet (929 m^3) area required.
16. Dried mixture is screened before transfer to curing/storage area. Provide 60 days curing/storage for screened compost; 6,000 square feet (557 m^2) area required.
17. Transfer screened wood chips to wood chip storage area.

Discussion

A process and materials flow diagram for the design example is shown in figure 8–3 and a conceptual layout for the system is shown in figure 8–4.

The overall space required is about 102,000 ft^2 (2.3 acres (0.93 ha)) which is about 0.5 acre per ton per day (0.22 ha/Mg/day) of dry sludge solids (8,400 wet tons (7620 Mg) per year) composted. Reducing or eliminating the bulking agent would significantly reduce the area required. Use of the extended pile configuration, instead of so many individual pads, would reduce the area required particularly in larger plants. By way of comparison, the Bangor, Maine, site is 65,000 ft^2 (1.5



LOCATION	DENSITY (lb/cu yd)	5 DAY PER WEEK OPERATION TONS PER DAY	CUBIC YARDS PER DAY
①	1800	32	36
②	500	5	21
③	700	22	63
④	1225	59	96
⑤	500	4	16
⑥	500	10	40
⑦	1100	73	133
⑧	835	49	117
⑨	865	22	50
⑩	700	27	77

Figure 8–3.—Process flow diagram. Composting sludge, 4 Mgal/d activated sludge plant.

acres (0.61 ha)) to compost 2,500 wet tons (2268 Mg) of sludge per year.

Control of moisture is the key to a successful sludge composting system. The sludge should be dewatered and/or mixed with sufficient bulking agent to obtain a moisture content of about 60 percent in the composting piles. The composted mixture should then be dried to about 40 percent moisture for efficient screening and handling for distribution.

Oxygen requirements are not high and the blowers or fans at all existing installations are operated intermittently. About 500 ft^3/hr per ton (15.6 m^3/Mg/hr) of dry sludge solids provided by a centrifugal fan, operating at 5 inches (127 mm) water pressure drop, is recommended based on the experience at Beltsville, Md.[15] The Bangor, Maine, system uses a 1/3-horsepower (0.25 kW) blower, rated at 335 ft^3/min (9.5 m^3/min) at 4 inches water pressure (102 mm), for each pile consisting of 50 cubic yards (38.2 m^3) sludge and 150 cubic yards (114.7 m^3) bulking agent.[8] The blowers are operated intermittently to maintain the oxygen level in the 5 to 15 percent range and to obtain as uniform temperature as possible.

The composting area should be paved. Probably the most efficient design in a permanent facility is to use fixed aeration and drainage systems. The aeration piping and drainage system could be placed in trenches in the composting pads and the blowers placed in permanent protected structures and equipped with water traps and controls.

Deodorizing piles should be replaced periodically. The deodorizing piles are replaced every other month at Bangor and the system has operated successfuly during cool weather with no deodorizing piles.

After the compost piles are formed, they should be covered with a layer of compost or wood chips for insulation and to prevent the outer edges from excessive drying and blowing dust. The insulating layer will also retain a significant amount of moisture from rainfall. Some of the operating facilities use a base layer of bulking agent or unscreened compost to cover the aeration piping. However, the piles are now constructed at

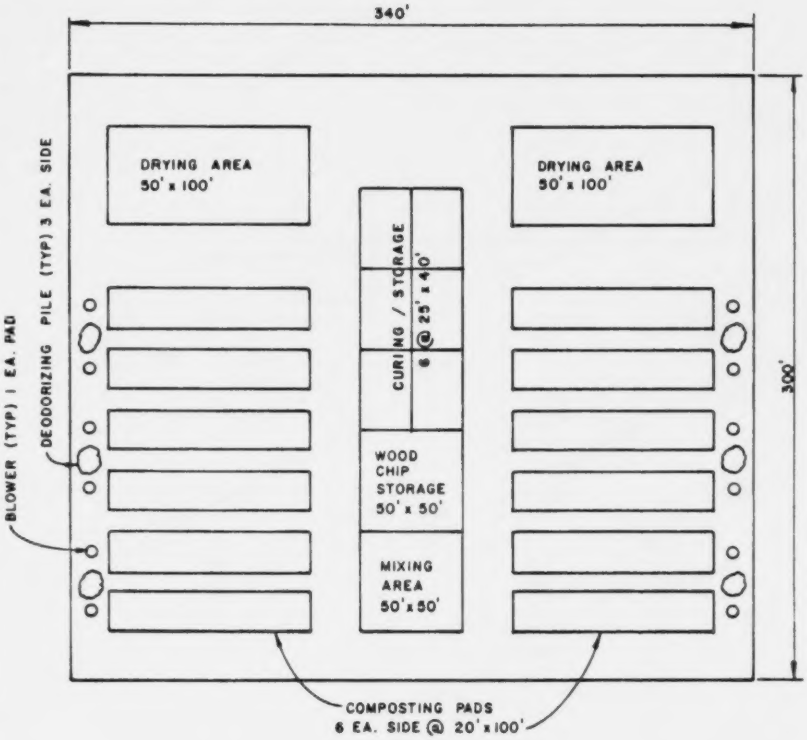


Figure 8–4.—Static pile forced aeration composting system plan (4 Mgal/d activated-sludge plant).

Bangor with no special base layer: the sludge-bulking agent mixture is placed directly on the aeration piping.

The existing composting facilities operate in uncovered areas, much of which are not paved. It may be desirable to cover the mixing, chip storage, curing/storage and drying areas; and cover and enclose the screening area. Runoff from the site must be controlled and runoff should be prevented from entering the composting pads.

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Chapter 9

Principles and Design Criteria for Sewage Sludge Application on Land

INTRODUCTION

Land application of sludge involves spreading wastewater solids on the soil surface or incorporating them into the root zone. Deep trenching or burying of sludge is discussed under "Landfilling."

The utilization of both sewage sludge and animal waste would require 1.3 percent of the cultivated land in the U.S.[1] Therefore, any concern about supply of land to utilize fully the increasing quantities of sewage sludge and animal waste being generated annually is not warranted.

Two distinct rates of application can be considered depending on the system objectives. If the objective is to recycle nutrients or apply sludge at agricultural rates, the nitrogen or heavy metal loadings will usually limit the application rates. Monitoring of soils and crops can be minimized when these rates are used. Higher loadings can be used when (1) detailed monitoring of environmental impacts is conducted, (2) uses such as reclamation of strip-mined land or application to forests or sod farms are considered, (3) nonfood chain crops are grown on the site.

The process of planning a land application project begins with collection of basic data on sludge, soils, climate, and regulations and involves selection, design, and operation of the site. Throughout the planning, support of local officials, farmers, and other key individuals must be sustained.

This chapter will briefly describe how to proceed with evaluating and implementing an agricultural sludge utilization program for a community. Because of the complexity of the topic, only an overview of the various considerations in implementing a sludge utilization program will be provided. In addition, two illustrative case studies are given as design examples. The material presented herein deals with sludge application to (1) agricultural soil growing crops consumed by humans or animals, and (2) nonagricultural areas such as parks, golf courses, forests, and median strips.

PRELIMINARY PLANNING

Obtain Local Support

Project implementation requires acceptance and approval by local officials, farmers, landowners, and other affected parties. Securing and maintaining local support is neither easy nor straightforward. Variations in local political, social, and economic conditions make meaningful generalizations difficult, but a few points are almost always applicable.

Obtaining local support requires some type of public involvement or participation program. These programs should promote public awareness by presenting an objective discussion of land treatment technology. Technical information should be presented in an easily understandable manner to insure communication between the public, engineer, planner, consultant, and other officials. If sludge is to be accepted willingly by the local residents, they must be informed early of the project and must be involved in its planning.

Public resistance can stem from concerns about the adverse impacts of using sludge for agricultural purposes. For example, there may be fear that a sludge may contain concentrations of organic or inorganic substances that could be toxic to plants or accumulate in plants to the detriment of animals or humans. Furthermore, inadequate treatment may produce a sludge that is a potential source of noxious odors or diseases. Objections by rural residents to landspreading might be encountered if they perceive the situation to involve an urban community imposing its waste disposal problem on the rural community. A large city is more likely to be seen as an outsider than a small city. Rural acceptance will be more readily forthcoming if local autonomy is assured and if the project has the apparent flexibility to incorporate needed changes.

Establishment of a public participation program requires answers to two basic questions:

1. Whose support should be obtained?
2. What methods of communication should be used?

Whose Support?

The initial task for obtaining public support is the selection of a project team, whose members can offer technical service and expertise.

Suggested personnel include:

1. Representatives of the city engineering or public works department to direct the project, manage one or more technicians or engineers from the city's staff, and coordinate activities with other committee members and outside consultants.

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2. The sewage treatment plant superintendent or consultant knowledgeable in treatment plant operations.
3. Local soil conservation service agent, agricultural extension service or forestry representatives to advise on site selection, management, soil and vegetation evaluation, and other matters.

The following individuals can be brought into the project as the need arises:

1. Private citizens, chamber of commerce representative, or newspaper editors to gage public acceptability of proposed program and/or implement a public education program to smooth the way for acceptance and adoption of the utilization program being formulated.
2. Outside consultants (university agriculture or forestry departments, agricultural extension services, private consultants) knowledgeable about soils, plants, chemistry, or sludge utilization problems and solutions.
3. A state regulatory agency representative or private engineering consultant conversant with detection, monitoring, evaluation, and mitigation procedures.
4. Legal advisors to draw up contracts, evaluate laws or regulations, or assist the city with implementation.

What Methods of Communication Should Be Used?

There are a variety of communication methods available for a public participation program. The most com-

Table 9–1.—Attitudes toward landspreading of sludge in five Ohio counties[2]

	Mean responses		
	Those who have spread (17 percent)	Those who haven't spread but have heard of spreading (45 percent)	Those who haven't spread nor heard of spreading (38 percent)
How would you react to spreading on your land [by local city]? .... 1 = enthusiastically 2 = favorably 3 = cautiously 4 = unfavorable 5 = opposed	2.50	3.05	[a]3.81
How would you react to [another] large city's proposal to spread on your land? .... 1 = enthusiastically 2 = favorably 3 = cautiously 4 = unfavorably 5 = opposed	2.85	3.48	[b]4.06
How would you feel about sludge being spread on neighbors' fields?... 1 = agreeable 2 = indifferent 3 = moderately opposed 4 = strongly opposed	1.75	2.00	[0]2.41
How would neighbors react to sludge spread on your land? .... 1 = agreeable 2 = indifferent 3 = moderately opposed 4 = strongly opposed	1.87	2.71	[c]3.12
Would you allow your land to be used as a demonstration site? .... 1 = Yes, I would be most happy. 2 = Yes, if rates are safe. 3 = No, spreading is all right but I don't want a site. 4 = No, my neighbors would be opposed. 5 = No, I am opposed to sludge spreading.	1.63	2.48	[a]3.24

[a] Responses are significantly different between groups at the 0.10 level.
[b] Responses are significantly different between groups at the 0.05 level.
[c] Responses are significantly different between groups at the 0.01 level.

mon are structured procedures such as public hearings, meetings, or workshops. Others are advertising or public relations techniques, such as press releases, pamphlets or brochures; and radio, television, or newspaper advertisement.

More fundamental than the actual organization of the participation program, are the basic attitudes of the project's proponents. Public participation should be viewed as an important and positive step in project planning rather than a necessary evil, obstacle, or delay tactic.

Because of the technical nature of the project, some amount of education is necessary by the planner to raise the public's level of expertise. The results of a survey in five counties in Ohio (table 9–1) revealed that landowners with prior experience in sludge spreading had significantly more favorable attitudes toward landspreading than those with no knowledge of spreading. This difference applied in cases where a local city was spreading on landowner's property and another larger city was spreading on landowner's property. Judgments of neighboring property owners followed similar patterns. No group of respondents was completely opposed to a demonstration project; however, those with less experience or less knowledge about sludge management were significantly less inclined to support such a project.[2] The manner in which this education effort is handled by the planner is an important factor in the success of the public participation program. Patience and tact will usually win out over arrogance and hard-sell salesmanship. Where resistance does arise, the situation may boil over if opponents are regarded only as uninformed, irrational or emotional.

In general, constructive public participation is occurring when there is open, two-way communication between public and project proponents. In a successful public participation program, all parties learn from each other and emerge from the planning effort reasonably satisfied with the final product.[3]

The most critical aspect of the entire sludge utilization program is involving the farmers or foresters, who will utilize the sludge, in the planning process. How this is to be accomplished is highly dependent on the individual communities involved; past experience with sludge application systems; overall public acceptance of the concept, and the extent to which related or tangential environmental concerns are voiced in the community.

Generally, a low-key approach is most effective. The various approaches can consist of one or more of the following:

1. Check with the sewage treatment plant to see if any local farmers have requested sludge in the past.
2. Have the local soil conservation service, forest service or agricultural extension service agent poll various individuals in the area for expressions of interest.
3. Describe the project in the local newspaper asking interested parties to contact the extension agent.
4. Telephone or personally visit the identified parties and solicit their participation.

Some of the salient points which need to be discussed with the landowners are:

1. How long are they willing to participate, i.e., a trial period of one or more years; open-ended until one or both parties decide to quit; or for a finite prescribed period of time?
2. What crops are traditionally planted and what is the prescribed crop rotation?
3. If the sludge were more amenable to a different crop, would they be willing to plant that particular crop?
4. Which fields would be included in the sludge spreading program?
5. Under what conditions would the landowner accept the sludge, what times of the year, and in what quantities?
6. Is the landowner willing to pay a nominal fee for the sludge, or is it necessary for the municipality to pay the landowner for taking the material?
7. Is the landowner willing to engage in special procedures, such as maintaining soil pH at 6.5 or greater?

Basic Data Collection

Any sludge utilization program must begin with basic data on the sludge itself, laws and regulation, climate, soil type, and land use. Data for specific alternative sites are discussed in "Site Selection."

Sludge Characteristics

Characterization of sludge properties is a necessary first step in the design of a land application system. Important characteristics include:

1. Current and future sludge generation quantities—cost estimates, land area requirements, site life, and application rates are all based in part on sludge production quantities.
2. Percent total and volatile solids—total solids content will influence the choice of transportation and application method. Volatile solids content is an important indicator of potential odor problems.
3. Nitrogen, phosphorus, and potassium—provides information on the fertilizer value of sludge. This information can be useful for determining optimum application rates, and the need for supplemental fertilization.
4. Heavy metals (principally cadmium, copper, nickel, lead and zinc) and specific organic compounds—provide information on limiting yearly or total application quantities.
5. Pathogens, parasites and viruses (optional)—evaluation of the above organisms is useful in assessing the degree of sludge stabilization.

Variability in Sludge Data

The physical and chemical properties of sludge are functions of numerous factors, including composition of the influent sewage, extent of industrial pretreatment, extent of nonpoint pollution sources, and type of sewage treatment. Because of these factors, sludge quantity and composition are highly variable among treatment plants. Furthermore, the daily fluctuations in sludge properties within a treatment plant are often greater than those found among plants.

The physical characteristics of sludge (quantity, percent solids, specific gravity, etc.) depend principally on the treatment processes used to generate the sludge. For instance, tertiary wastewater treatment will increase the quantity of sludge by almost an order of magnitude over conventional methods. In addition, the chemical composition of sludge is affected by handling methods. Heat drying, for example, will decrease NH_4^+ levels, but will leave absolute quantities of K^+ or Na^+ unchanged. The effect of wet-air oxidation on sludge composition is shown in table 9–2, while the differences among aerobically and anaerobically digested sludges and other sludge types are shown in table 9–3.

The large variations in sludge metal content are illustrated in table 9–4. This variability may be a reflection of the extent of metal-using industries served by the treatment plant. However, not all cities exhibit such fluctuations (i.e., certain suburban "bedroom" communities).[4]

Many cities may have instituted pretreatment measures to reduce concentrations of heavy metals in sewage. The effect of such pretreatment is shown by the example in table 9–5. Heavy metal loads decreased in both the wastewater and sludge after pretreatment.

The data shown in tables 9–2 through 9–5 are used primarily for illustrative purposes. While useful for order-of-magnitude estimates and preliminary planning, application of the figures to any specific treatment plant for design purposes is not warranted.

Data Sources

The wastewater treatment plant represents the best source of sludge data. If data have not been collected, a sampling procedure should be instituted as discussed below. In addition, other agencies or individuals should be located who have analyzed similar samples and who can make their findings public. Possible sources are:

1. State Regulatory Agencies.
2. National Pollutant Discharge Elimination System (NPDES) Report.
3. Local or state public health departments.
4. Local universities.
5. Environmental Protection Agency, Washington, D.C., or regional office.

Sampling and Analysis

The flow weighted average chemical composition of sludge is desirable and requires continuous flow mea-

Table 9–2.—Effect of wet-air oxidation on the chemical composition of sewage sludges[5]

Parameter	Plant No. 1		Plant No. 2	
	Before	After	Before	After
		percent[a]		
Volatile solids	47.1	36.7	57.2	36.3
Soluble P	0.082	0.004	0.153	0.010
Particulate P	1.074	1.219	1.401	2.315
Soluble total N	1.356	0.471	1.354	0.427
Soluble organic N	0.293	0.173	0.131	0.170
Particulate total N	2.120	0.856	2.839	1.348
Particulate organic N	1.837	0.863	2.490	1.329
		mg/kg[a]		
Total Cu	1,090	1,011	649	852
Total Zn	1,996	1,974	1,814	2,497
Total Ni	70	70	911	1,064
Total Cd	11.4	11.3	58.4	77.2
Total Pb	451	471	686	978

[a] Percent or mg/kg oven-dry solids basis.

Table 9–3.—Median concentrations of major constituents in sewage sludge versus digestion method[6]

Component	Type of sludge			All sludges
	Anaerobic	Aerobic	Other[a]	
		Percent		
N	4.2	4.8	1.8	3.3
P	3.0	2.7	1.0	2.3
K	0.3	0.4	0.2	0.3
Na	0.7	0.8	0.1	0.2
Ca	4.9	3.0	3.4	3.9
Mg	0.5	0.4	0.4	0.4
Fe	1.2	1.0	0.1	1.1
Al	0.5	0.4	0.1	0.4
		mg/kg		
Pb	540	300	620	500
Zn	1,890	1,800	1,100	1,740
Cu	1,000	970	390	850
Ni	85	31	118	82
Cd	16	16	14	16
Cr	1,350	260	640	890

[a] Lagooned, primary, tertiary.

Table 9–4.—Chemical composition[a] of sewage sludges[6]

Component	Units	Number of samples	Range	Median	Mean	Coefficient of variability, percent[b]
Total N	Percent[c]	191	0.1–17.6	3.3	3.9	85
NH_4-N		103	0.1– 6.8	0.1	0.7	171
NO_3-N		45	0.1– 0.5	0.1	0.1	158
P		189	0.1–14.3	2.3	2.5	61
K		192	0.1– 2.6	0.3	0.4	99
Ca		193	0.1–25.0	3.9	4.9	87
Mg		189	0.1– 2.0	0.5	0.5	75
Fe		165	0.1–15.3	1.1	1.3	148
Mn	mg/kg[c]	143	18– 7,100	260	380	209
B		109	4– 760	33	77	162
Hg		78	0.5–10,600	5	733	232
Cu		205	84–10,400	850	1,210	138
Zn		208	101–27,800	1,740	2,790	134
Ni		165	2– 3,520	82	320	162
Pb		189	13–19,700	500	1,360	177
Cd		189	3– 3,410	16	110	157

[a] Data are from numerous types of sludges (anaerobic, aerobic, activated, lagoon, etc.) in seven states: Wisconsin, Michigan, New Hampshire, New Jersey, Illinois, Minnesota, Ohio.

[b] Standard deviation as a percentage of mean. Number of samples on which this is based may not be the same as for other columns.

[c] Percent or mg/kg oven-dry solids basis.

Table 9–5.—Effect of pretreatment[a] of plating shop wastewater on sludge composition[4]

Element	Plating shop wastewater, mg/l		Digested sludge mg/kg dry sludge			
	7/75	4/76	4–5/75	7/75	11/75	4/76
Zn	880	4.2	5,470	5,060	3,650	3,030
Cd	29.6	0.034	190	178	90	50
Cu	17.2	0.095	1,500	1,590	1,440	1,370
Ni	138.0	2.08	1,120	1,080	460	410
Pb	9.2	0.071	340	360	310	305
Cr	1.85	—	—	2,590	1,030	—

[a] Pretreatment began in July 1975.

surements in conjunction with periodic sampling for chemical analyses. Even though this approach is preferred, it is difficult to implement, resulting in the tendency to collect grab samples.

For design purposes, the median concentration obtained from analyses of several grab samples may prove more useful than average chemical composition. The median, unlike the mean, tends to minimize data from samples exhibiting abnormally high or low concentrations and may therefore prove more representative. The number of samples needed to estimate the median concentrations should be based on the residence time of the sludge in the digester or process used. Seasonal variations of inputs to the plant should be considered when establishing the time and frequency of sampling.

Other pertinent points of sludge sampling can be summarized as follows:

1. Develop a sound sampling program. A minimum effort is 3 to 6 samples obtained over a one-year period. The number of samples required can vary from plant to plant and varies as a function of desired accuracy and precision. The validity of recommendations for application rates is directly proportional to the knowledge of sludge composition.
2. Sample the form of sludge being considered for land application.
3. Consider the residence time of sludge in the treatment plant when deciding the frequency of sampling.

Samples must be preserved to prevent changes in composition between time of collection and analysis. Freezing and low temperature storage (4°C) are recommended for samples to be analyzed >7 and <7 days, respectively, after collection.

To minimize nitrogen volatilization prior to analysis, all N analyses should be performed at ambient moisture levels. For liquid sludges (<10 percent solids), subsampling is facilitated by placing the sample in a blender to disrupt solid particles. For sludges containing >10 percent solids, dilution of the sludge sample with H_2O and then disruption in a blender may alleviate subsampling problems. All other analyses (P, K and metals) can be performed on samples dried at room temperature or in an oven. After drying, the sludge should be ground to <60 mesh to allow accurate subsampling. The percent solids content of each sludge analyzed is obtained in order to express all data on an oven-dry solids basis.

Climate

Precipitation, evapotranspiration, temperature, and wind data can be used to determine (1) length of growing season, (2) number of days when sludge cannot be applied, and (3) storage requirements. For cases where design application rates are governed by nitrogen uptake rates, a limited growing season will require long periods of storage or alternative methods of winter disposal. Storage capacity considerations must also include periods of inclement weather and frozen ground when sludge cannot be applied.

The length of the growing season affects the amount of time a site can be used for application. The length of the growing season for perennial crops is generally the period beginning when the maximum daily temperature stays above the freezing point for an extended period of days, and continues throughout the season despite later freezes.[7] This period is related to latitude and hours of sunlight as well as to the net flow of energy or radiation into and out of the soil.

Sufficient climatic data are generally available for most locations from three publications of the National Oceanic and Atmospheric Administration (NOAA—formerly the U.S. Weather Bureau).

The *Monthly Summary of Climatic Data* provides basic data, such as total precipitation, maximum and minimum temperatures, and relative humidity, for each day of the month for every weather station in a given area. Evaporation data are also given where available.

The *Climatic Summary of the United States* provides 10-year summaries of data in the same given areas. These data are convenient for use in most of the evaluations, and includes:

1. Total precipitation for each month of the 10-year period.
2. Total snowfall for each month of the period.
3. Mean number of days with precipitation exceeding 0.10 and 0.50 in. (0.25 and 1.3 cm) for each month.
4. Mean temperature for each month of the period.
5. Mean daily maximum and minimum temperatures for each month.
6. Mean number of days per month with temperature less than or equal to 32°F (0°C), and greater than or equal to 90°F (32.5°C).

Local Climatological Data, an annual summary with comparative data, is published for a relatively small number of major weather stations. Among the most useful data contained in the publication are the normals, means, and extremes which are based on all data for that station, on record to date. To use such data, correlation may be required with a station reasonably close to the site.

Climatic data should be subjected to a frequency analysis to determine the expected worst conditions for a given return period. Such analyses for rainfall for selected cities appears in a recent EPA publication.[8]

Regulations

State and Local

Information on regulations governing sludge generation and disposal can be obtained from the state wastewater and/or solid waste regulatory authority in the state. The state or local public health departments can also provide information on local acceptability of sludge utilization as well as detailed information on public health related aspects of sludge disposal. Other sources of regulatory information include agricultural colleges, solid waste management agency, or water-quality agency. State and local regulations can often provide a variety of other useful information.

Most states have not set policies regarding use of sludge on land, but many states have recently issued guidelines or are preparing to do so. Some of these are regulatory documents, while others are information bulletins.

Local control of land use can affect site selection for sludge application. Small communities usually apply sludge to farmers' land; thus, sludge use is apt to be considered an agricultural practice. Big cities that buy or lease land and apply sludge at rates higher than necessary to fertilize a crop may face legal restraints. Zoning ordinances may restrict landspreading by a city on land outside its corporate limits.

Federal

On November 2, 1977, the U.S. Environmental Protection Agency (EPA) published a technical bulletin entitled "Municipal Sludge Management: Environmental Factors."[9] This technical bulletin is intended to assist the Agency's Regional Administrators and their staffs in evaluating grant applications for construction of publicly owned sewage treatment works under section 203(a) of Public Law 92–500. The bulletin, while not a regulatory document, addresses factors important to the environmental acceptability of particular sludge management options and allows maximum flexibility to the regions. The document emphasizes land application alternatives since no

Agency guidelines have been issued. It does state, however, that priority should be given to application of sludge on nonagricultural lands (e.g., parks, forests, strip-mine reclamation, etc.).

The bulletin places primary reliance on the Food and Drug Administration (FDA) and the U.S. Department of Agriculture (USDA) to establish recommendations for acceptable tolerances for heavy metals and other contaminants in plants. Technical assistance needed to resolve specific questions concerning sludge use is available from these and other agencies. To obtain funds from the construction grants program, a proposed project must follow the guidelines set forth in the bulletin.

While the technical bulletin is not a regulatory document, new solid waste legislation (the Resource Conservation and Recovery Act of 1976 (PL 94–580, or RCRA), may result in the regulation of some municipal sludge. This law provides the Federal Government with the authority to protect health and the environment and facilitate resource recovery and conservation in the face of the growing solid waste disposal problem.

The definitions of solid waste or solid waste management stated in RCRA refer to sludge and sludge management. Furthermore, the definition of disposal, which includes placing waste *into* or *on* any land, clearly encompasses both sludge landspreading and sludge disposal in a landfill. The definition of hazardous waste also leaves open the possibility that some sludges, like some solid wastes, may be hazardous and may, therefore, be covered under the hazardous waste control program of Public Law 94–580 (subtitle C).

Sections dealing with residual sludge management are summarized as follows:

1. *Guidelines* (section 1008)—The guidelines will likely include descriptions of alternative sludge management practices which will achieve acceptable environmental performance levels.
2. *Hazardous Wastes* (subtitle C)—If some sludges are defined as hazardous wastes, this subtitle will affect sludge management.
3. *Planning and Open Dumps* (subtitle D)—Some current sludge disposal practices may fall under the definition of open dumps, and therefore, will be regulated by this act.

SITE SELECTION

Site selection procedures normally begin after it has been established, by rough estimate, that sufficient land area is available for a sludge utilization program. Selection procedures normally include an areawide evaluation of soils, geology, hydrology, topography, and land use. In addition, potential site accessibility and proximity to treatment plant are also considered. The following sections discuss the above factors as well as preliminary screening, site identification, and site acquisition procedures.

Preliminary Screening

To obtain an initial estimate of the area required for land application, the total quantity of sludge must be known or estimated. This number, when divided by an assumed application rate, will provide an estimate of total acreage needed. Initial values of 5 and 10 dry tons/acre/yr (11.2 and 22.4 Mg/ha/yr) can be considered as estimates for forested and agricultural lands, respectively. These numbers can be modified during later stages of the design process, when other site specific factors have been demonstrated.

After estimation of total acreage required, potentially available land areas within a radius of up to about 30 miles (48 km) of the treatment plant can be considered, including croplands, forests, parks, golf courses, strip-mined areas, and other arable lands. Local extension agents and county planners can often aid in the selection process.

Not all land will be suitable for land application of sludge. The use of soil survey maps can provide screening of potentially unsuitable areas, such as:

1. Steep areas having sharp relief and slopes greater than 12 percent.
2. Land adjacent or close to urban/suburban development.
3. Rocky, nonarable land (unless reclamation is being considered).

In addition to these physical factors, local officials' experience with similar projects, such as locating a site for a sanitary landfill for refuse disposal, may be useful. Certain areas may not be available because of historical resistance to such projects. Such resistance may be intensified if sludge hauling requires crossing political boundaries. In other words, the aforementioned 30-mile (48 km) radius circle should not fall within another city or county.

This type of initial screening procedure takes only a few days but could save months of potentially unnecessary work at a later time. If enough land appears to be available, more detailed planning can get underway; otherwise other sludge handling alternatives can be investigated.

Site Identification

Once the preliminary screening has been accomplished, a more detailed study of potential sites can be initiated. Land use, topography, and soil properties represent three factors useful for excluding undesirable areas and identifying best suited sites. Limiting criteria can be set for each factor with the understanding that they would be reexamined if excessive amounts of land were excluded from consideration.

Land Use

Prevailing land use may exert a significant influence on the acceptability of sludge spreading. Basic land uses such as agriculture, urban-suburban, commercial, or industrial, along with size of holdings and type of farming should be considered. For example, small land holdings in a community with a large nonfarm population serve to restrict landspreading options. Areas devoted to row crop production restrict the periods when sludge can be applied to land. In contrast, sludge can be spread on grasslands or forests throughout much of the year. The methodology and management practices for using sludge for forest production and disturbed land reclamation are only now being developed, but it appears that the opportunity to use sludge beneficially in these areas has been largely overlooked.

Land use considerations also involve identification of areas with which land application of sludge may not be compatible. Examples are housing or commercial development, and areas of historical, archeological, or ecological significance.

The local government's planning and/or zoning department is the best source of general land use data. The local Soil Conservation Service or Agricultural Extension Service representative has knowledge of both the farms and types of crops typically planted. The agent will, in most cases, have a comprehensive, up-to-date county soil survey with aerial photo maps showing the land area, and describing the soil types, including physical and mechanical properties of the soil, best land use, and other pertinent farming information.

Often a real estate broker will have handy community or areawide maps indicating the tract of land, present owners, and property boundaries. The county recorder or title insurance company is another useful source of information on property ownership, size of tracts and related information.

Detailed information on current cropping practices can be obtained from the local Soil Conservation Service or Agricultural Extension Service representative, or from university or college departments of agronomy. These people have extensive field experience and are quite knowledgeable about many aspects of soils, cropping practices, toxic or deficient constituent levels, and farm management. The agricultural colleges have done considerable work on the impacts of sludge on plants and soils. Related disciplines such as departments of horticulture, forestry, agronomy, soil science, or others can be consulted as the need arises.

Topography

Topography asserts a major influence on surface and subsurface water movement, soil erosion, and soil formation processes. Slope characteristics are important factors in determining the amount of runoff and erosion. Erosion is a minimal problem on flat lands, but with increasing slope the potential for erosion increases. The degree, length, uniformity, and shape of the slope are all important in determining the relative ease of establishing suitable erosion-control practices.

The percent slope is usually more important than length from the standpoint of erosion severity. The effect of slope length on erosion varies considerably with the type of soil. Generally, longer slopes have less runoff than shorter ones, especially for permeable soils.

Regardless of slope, certain conservation practices can be adopted which will minimize runoff from sludge-treated soils. Such practices include reduced tillage systems, terraces, strip cropping, and retention of crop residues on the soil surface wherever possible.

Two general landscape drainage systems exist: the open and the closed system.[10] The open drainage system of most humid and subhumid areas permits the movement of sediment and soluble material from a given site to the watercourse. In contrast, the closed drainage system of some arid and semi-arid areas is a landscape where essentially all products derived within the perimeter are trapped within the system and are not transmitted to major streams or underground water supplies. Excess water is ponded and then evaporates or percolates through the soils. These systems contribute little to the pollution of the environments outside their perimeter. A modified closed system can easily be developed on a nearly level landscape by erection of small ridges across the outlet of the drainage basin.

At any proposed site requiring major shaping, the characteristics of the subsoil horizons should be carefully evaluated to determine the types of chemical and physical characteristics which may be exposed or brought closer to the surface during the shaping operation.

Soils on convex landscape positions or on steep slopes usually are well drained, well oxidized, thinner, and subject to erosion. Soils on concave landscape positions and on broad flats are often more poorly drained, less well oxidized, and deeper. Water and sediment from higher positions move to these low-lying landscape areas.

Therefore, a closed or modified closed drainage system would be preferred with slopes less than 4 to 6 percent. Steeper gradients may be acceptable where management application methods reduce erosion hazards.

Slope data may also be obtained from U.S. Geological Survey topographic maps. In flat areas these maps are plotted with one-foot contour intervals. The U.S. Soil Conservation Service soil surveys also delineate soils by slope.

Soils

The feasibility of sludge utilization is influenced by the nature of the soils on which the sludge is applied. When soil properties are known and properly considered, sludge can be applied to land beneficially. Soils with a wide range in physical, chemical, and biological characteristics can be used successfully if the system is designed to compensate for less-than-ideal properties.

Soils can be characterized by the following physical properties:

1. Permeability.
2. Drainage.

3. Runoff and flooding.
4. Available water capacity.

These soil characteristics are discussed in the following paragraphs and are summarized in tables 9–6, 9–7, and 9–8.

Permeability

Soil permeability influences the length of time wastes remain in the soil and potential loading rates.[11] The rate at which soils will take in water is a function of the size, shape, and number of their pores.

Drainage

Soil drainage is a measure of the length of time the soil is naturally at or near saturation during the growing season.[12] This reflects both the ability of the soil to remain aerobic and to support traffic.

Runoff and Flooding

It is important that the applied waste stay on the site. Runoff is closely related to infiltration rate, soil slope, and cover. In general soils that flood are considered to have severe limitations for disposal of wastes. If the

Table 9–6.—Limitations of soils for application of biodegradable solids and liquids (nationwide, interim)[13–15]

Item affecting use	Soil-limitation rating		
	Slight	Moderate	Severe
Permeability of the most restricting layer above 60 in.[a]	0.6–6.0 in./hr	6–20 and 0.2–0.6 in./hr	>20 and <0.2 in./hr
Soil drainage class[16]	Well drained and moderately well drained	Somewhat excessively drained and somewhat poorly drained	Excessively drained, poorly drained, and very poorly drained
Runoff[16]	Ponded, very slow, and slow	Medium	Rapid and very rapid
Flooding	None	None for solids; only during nongrowing season allowable for liquids	Flooded during growing season (liquids) or anytime (solids)
Available water capacity from 0–60 in. or to a root-limiting layer	>8 in. (humid regions) >3 in. (arid regions)	3–8 in. (humid regions) Moderate class not used in arid regions	<3 in. (humid regions) <3 in. (arid regions)

[a] Moderate and severe limitations do not apply for soils with permeability <0.6 in./hr: (1) for solid wastes unless the waste is plowed or injected into the layers having this permeability or evapotranspiration is less than water added by precipitation and irrigation, and (2) for liquid wastes if layers having that permeability are below the rooting depth and evapotranspiration exceeds water added by precipitation and irrigation.

Table 9–7.—Soil limitations for sewage sludge to agricultural land at nitrogen fertilizer rates in Wisconsin[17]

Soils features affecting use	Degree of soil limitation		
	Slight	Moderate	Severe
Slope[a]	Less than 6 percent	6 to 12 percent	More than 12 percent
Depth to seasonal water table	More than 4 ft	2 to 4 ft	Less than 2 ft
Flooding and ponding	None	None	Occasional to frequent
Depth to bedrock	More than 4 ft	2 to 4 ft	Less than 2 ft
Permeability of most restricting layer above 3 ft	0.6 to 2.0 in./hr	2.0 to 6.0 in./hr 0.2 to 0.6 in./hr	Less than 0.2 in/hr More than 6 in./hr
Available water capacity	More than 6 in.	3 to 6 in.	Less than 3 in.

[a] Slope is an important factor in determining the runoff that is likely to occur. Most soils on 0 to 6 percent slopes will have very slow or slow runoff; soils on 6 to 12 percent slopes generally have medium runoff; and soils on steeper slopes generally have rapid to very rapid runoff.

Table 9–8.—Soil suitability for sludge applications for agricultural production in New York State[13]

Item affecting use	Soil potential				
	Very good	Good	Moderate	Poor	Very poor
Drainage class and approximate depth in inches to permanent or fluctuating water table	Well drained (>36)	Moderately well drained (18–36)	Somewhat poorly drained (12–18)	Poorly drained	Very poorly drained (<6)
Total water-holding capacity [in. H_2O/rooting depth]	>6	4–6	3–4	2–3 <2	
Slope (percent)	<3	3–8	8–15	15–25	>25
Rooting depth (in. to root restricting horizon)	>40	30–40	20–30	10–20	<10
Trafficability (unified soil group)	GW, GP, SW, SP, GM, GC, SM, SC, Pt (drained)	CL with PI <15	ML, CL with PI >15	OH, OL, MH	CH, Pt (undrained)
Permeability class (in./hr in least permeable horizon)	0.6–2.0	2.0–6.0	>6.0	0.6–0.06	<0.06
Erosion	None to slightly eroded	Slightly eroded	Moderately eroded	Severely eroded	Very severely eroded
Stoniness and rockiness	0	1	2	3	4 and 5
pH in B horizon	>7.0	6.5–7.0	6.0–6.5	5.5–6.0	<5.5
Texture	si1	1, sic1	s1, c1	sc1, c	s, 1s (not irrigated)

soils flood only during the nongrowing season, however, they are considered as having only moderate limitations in some localities.

Very few soils are totally unsuitable for land application of sludge. Some, however, are better than others. The U.S. Soil Conservation Service (SCS) and several states have developed tables which rate the suitability of soils for receiving sewage sludge. Table 9–6 shows the guidelines prepared by the SCS while tables 9–7 and 9–8 are for Wisconsin and New York, respectively.

Tables such as these should be consulted to determine whether a potential site is suitable for land application. However, additional onsite investigations should be conducted for specific site selection and for system design.

The soil is rated by the single most severe characteristic. The categories can be quite restrictive since one poor characteristic forces a soil into the most limiting category. Nevertheless, the method enables the planner to quickly determine the best and worst soils. For example, as a first approximation, all soils in the "severe" rating of table 9–6 can be eliminated.

Geology

The movement of water into and through groundwater aquifers is dependent on local and regional geology. For sludge application systems requiring groundwater monitoring, a knowledge of subsurface conditions is essential.

Bedrock characteristics can influence the direction and speed of groundwater movement and determine whether a pollutant might be carried large distances with only minimal biological or chemical renovation.

For example, limestone bedrock can be interlaced with a complex pattern of relatively open fractures and solution channels. The fractures and channels can behave like open pipelines. Any contaminant which enters such an opening can travel substantial distances without any significant reduction in concentrations. Under such conditions, the discharge of the solution channel water into a well or stream could result in pollution problems.

In evaluating the hydrogeologic conditions associated with a specific site, the following factors should be considered:

1. Depth to the groundwater table.
2. Seasonal water table fluctuations.
3. Groundwater velocity.
4. Direction of travel.
5. Present and potential use of groundwater and surface water bodies.
6. Existing surface and groundwater quality.
7. Interrelationship between ground and surface water bodies.
8. Surface water body ecology.
9. Subsurface soil and rock characteristics which affect groundwater movement patterns and quality.[18]

Site Delineation and Evaluation

Following exclusion of unsuitable areas, specific sites can be chosen. Since modes of transportation and transportation distances are important to the economics of sludge utilization, it is desirable to choose sites as close as practical to the generating sewage treatment plant. Using a regional map, concentric rings of incremental radii can be drawn around the sewage treatment plant. Candidate sites within each concentric ring can then be identified. Sites within the inner ring have the highest priority rating while sites more distant from the source become progressively less attractive.

Each site can then be evaluated on the basis of soil criteria presented in tables 9–6, 9–7, or 9–8. Factors listed below should also be considered.

1. Proximity of disposal areas to homes, commercial establishment, town center, etc.
2. Ready access from all-weather roads.
3. Prevailing wind direction for minimization of odor complaints.
4. Distance to groundwater or nearest surface water body.
5. Total farm acreage available on each farm.
6. Types of crops historically planted.
7. Prevailing soil types present with regard to their suitability for sludge additions.
8. Field slopes and general site topography.

Ranking or scoring procedures and/or overlay techniques can be used to help select the best sites. For example, transparent map overlays can be prepared for each criterion discussed above. Thus, the first map might have areas with steep slopes shaded; the second map would have urbanized and other excluded areas shaded. Subsequent maps would have other restrictions as shaded areas. Information from all maps would then be combined to produce a composite map; the best areas for land application would have the lightest shading or none at all.

Site Acquisition

Site acquisition represents the most critical step in the implementation of a land application project. The points discussed in "Preliminary Planning" are essential groundwork for obtaining public support and acquiring the most desirable sites.

A variety of contractural arrangements exist between sludge producers and landowners. The most common arrangements between municipalities and farmers in descending order of frequency of occurrence are:

1. The city transports and spreads the sludge at no expense to the farmer.
2. The city not only transports and spreads the sludge, but pays the farmer a nominal sum of 50 cents to $2.00 per load. This is usually only for sites which are close to the treatment plants or do not generate a particularly desirable sludge.
3. The farmer pays a nominal fee of between $1 and $2 per load. The city transports and spreads the sludge. This is most common where there is a large local demand for the sludge or the sludge is of particularly good quality.
4. The city leases the site for a period of 1 to 5 years.

Less common arrangements are:

1. Outright purchase of the site. The advantage of this is that the city has considerable control over both the quantity and frequency of application, as well as the crops grown on the site.
2. Contractual arrangement between the city and the receiving farmers. The sludge is distributed on a rotating basis to each of the participants. In at least one system, payment of an initial sum of money provides a commitment on the part of the farmer.

Written rather than oral contracts are preferred. With written contracts there is less chance of ambiguity and misunderstandings between parties. Despite the best intentions of either party, oral contracts can often result in different interpretations of the conditions of the agreement (i.e., application rates, crops grown, etc.).

A survey of several Ohio communities revealed that only 20 percent had written contracts.[2] Most of those contracts had one or more of the following points:

1. "Escape" clause for either party
2. Restriction to the type of crops grown on the disposal site
3. Restrictions on application during growing season and on application to wet soils
4. Restrictions on application rate
5. Placement of any liabilities due to odor, runoff, etc. with the farmer.

The last provision would seem unfair to the farmer recipient unless the analysis of the sludge is known by the farmer. Making the farmer solely liable for the effects of the sludge would be equitable only when the treatment plant is able to provide a detailed analysis of the sludge and is assured that the farmer has been informed of the potential hazards of application.

PROCESS DESIGN

Process design involves the selection of suitable crops, determination of sludge application rates, and choice of application method. Although basic design goals (maximization of crop yield and quality, and minimization of environmental damage) remain constant regardless of projected land use, design procedures differ for application on agricultural, forested, reclaimed, or parklands. Design procedures for agricultural lands are based on principles developed from soil fertility research in conjunction with results from sludge utilization studies. In contrast, a minimal amount of information is available concerning sludge application to forested, reclaimed, and

Table 9–9.—Annual N, P, and K utilization by selected crops[a]

Crop	Yield/acre	N	P	K
		(lbs/acre)		
Corn	150 bu.	185	35	178
	180 bu.	240	44	199
Corn silage	32 tons	200	35	203
Soybeans	50 bu.	[b]257	21	100
	60 bu.	[b]336	29	120
Grain sorghum	4 tons	250	40	166
Wheat	60 bu.	125	22	91
	80 bu.	186	24	134
Oats	100 bu.	150	24	125
Barley	100 bu.	150	24	125
Alfalfa	8 tons	[b]450	35	398
Orchard grass	6 tons	300	44	311
Brome grass	5 tons	166	29	211
Tall fescue	3.5 tons	135	29	154
Bluegrass	3 tons	200	24	149

[a] Values reported are from reports by the Potash Institute of America and are for the total above-ground portion of the plants. For the purpose of estimating nutrient requirements for any particular crop year, complete crop removal can be assumed.

[b] Legumes obtain N from symbiotic N_2 fixation so fertilizer N is not added.

other nonagricultural lands. Design procedures for agricultural and nonagricultural lands are discussed separately in this chapter.

Agricultural Lands

Type of Crop

It is usually advantageous to maintain or utilize the normal cropping patterns found in the community.[19,20] These patterns have evolved because of favorable soil, climatic, and economic conditions and will probably maintain certain advantages in the sludge application system as well. One possible exception could occur if the cropping pattern were restricted to a single crop. In this case, additional crops could increase the opportunity of applying sludge during a variety of seasons.

Row crops such as corn and soybeans probably offer the least sludge application flexibility, but can be used on sludge amended soils with few constraints. Corn has an added advantage in that it accumulates little cadmium. Forage crops can be superior to others in terms of nutrient utilization during the growing season. Removal of these grasses from the site maximizes nutrient reuse. However, a continuous sod makes sludge applications more difficult. Small grain crops use lower amounts of nutrients as compared to row crops or forages, and are subject to lodging. Vegetables, especially leafy and root

Table 9–10.—Removal of different elements from soils by crops[21]

Crop	Yield per acre	Removal (lbs/acre)							Conc (mg/kg)			
		N	P	K	Ca	Mg	S	Na	Fe	Mn	Cu	Zn
Corn grain	100 bu	80	15	17	2	8	7	1	66	14	6	43
Grain sorghum	80 bu	80	14	15	2	8	7	2	90	30	20	28
Soybeans	32 bu	105	11	29	5	5	4	4	70	26	14	—
Peanuts	2,500 lbs	94	8	12	2	4	6	14	16	—	—	—
Cottonseed	1,800 lbs	62	13	20	3	6	4	5	114	10	41	—
Wheat	60 bu	81	15	18	2	4	6	3	73	80	11	23
Rice	6,000 lbs	78	14	9	3	4	3	3	96	48	9	5
Barley	75 bu	67	15	20	3	5	6	1	87	26	12	25
Sugarbeets	25 t	21	20	125	20	15	1	40	227	765	30	—
Corn silage	20 t	136	24	118	34	24	12	3	929	228	47	98
Alfalfa hay	7 t	332	31	212	197	38	43	19	1,306	282	74	92
Coastal bermuda hay	9.5 t	243	29	270	74	27	—	—	—	—	—	—
Reed canarygrass hay	7 t	169	30	282	41	31	—	47	816	503	65	—
Potatoes	30 t	210	30	288	6	18	12	12	544	240	102	—
Tomatoes	20 t	71	11	98	5	6	—	1	92	—	—	—
Lettuce	12.5 t	34	5	42	5	3	—	2	55	—	—	—
Carrots	20 t	58	12	112	12	8	8	15	104	68	24	—
Snap beans	5 t	27	4	21	5	3	—	1	32	—	—	—
Dry beans	1,800 lbs	64	8	22	3	3	4	1	64	15	8	—
Loblolly pine	annual growth	9	1	4	5	2	1	—	—	—	—	—

vegetables, are not recommended on sludge amended soils because they are heavy metal accumulators.

Nutrient Requirements

Fertilizer recommendations for crops are based on the nutrients needed for the desired yield. The amounts of N, P, and K required by the major agronomic crops are shown in tables 9–9 and 9–10. Plant available nutrient levels in the soil before planting will dictate the fertilizer additions for a desired yield as illustrated in table 9–11.

Table 9–11.—Fertilizer P and K recommendations for various yields of corn[a]

Available nutrient level in soil	Yield level, lb/acre				
	100–110	111–125	126–150	151–175	176–200
lbs P/acre	Fertilizer P needed, lbs/acre				
0–10	44	48	55	57	66
11–20	31	35	40	44	53
21–30	22	26	26	31	35
31–70	13	13	18	22	22
>70	0	0	4	4	4
lbs K/acre	Fertilizer K needed, lbs/acre				
0–80	83	100	125	149	166
81–150	58	75	100	116	133
151–210	42	50	58	75	100
211–300	25	25	33	50	66
>300	0	0	0	0	0

[a]Purdue University Plant and Soil Testing Laboratory Mimeo, 1974.

The previous year's crops may exert an influence on the nutrient recommendations for a crop at different yield levels as shown in table 9–12. Figures 9–1 and 9–2 relate plant yield to nutrient concentrations. Recommendations for sludge application stress utilization rates consistent with nitrogen uptake by a crop.

Application Rate

Sludge application rates recommended for crop production are calculated in the same manner as commercial fertilizer application rates. At these rates, sludges can be considered as strictly a low grade fertilizer.

Annual application rate recommendations for agricultural soils are based on the nitrogen and cadmium contents of a sludge and the crop being grown. The total amount of sludge applied to soils is limited by the heavy metal additions with zinc, copper, nickel, and cadmium

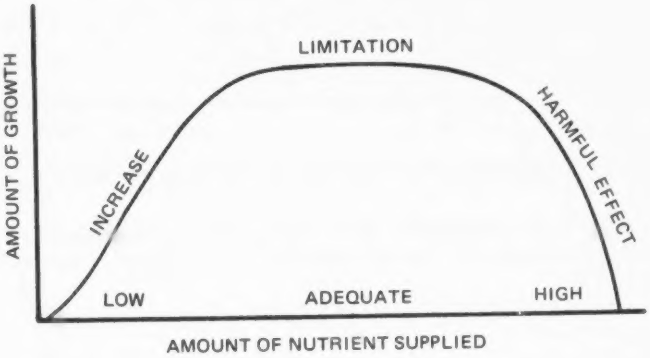


Figure 9–1.—General relationship between any particular nutrient or growth factor and plant growth.

Table 9–12.—Influence of previous crop of N fertilization rates for corn.[a]

Previous crop	Yield level (bu/acre)				
	100–110	111–125	126–150	151–175	176–200
			lbs N/acre		
Good legume (alfalfa, red clover, etc.)	40	70	100	120	150
Average legume (legume-grass mixture or poor stand)	60	100	140	160	180
Corn, soybeans, small grains, grass sod	100	120	160	190	220
Continuous corn	120	140	170	200	230

[a]Purdue University Plant and Soil Testing Laboratory Mimeo, 1974.

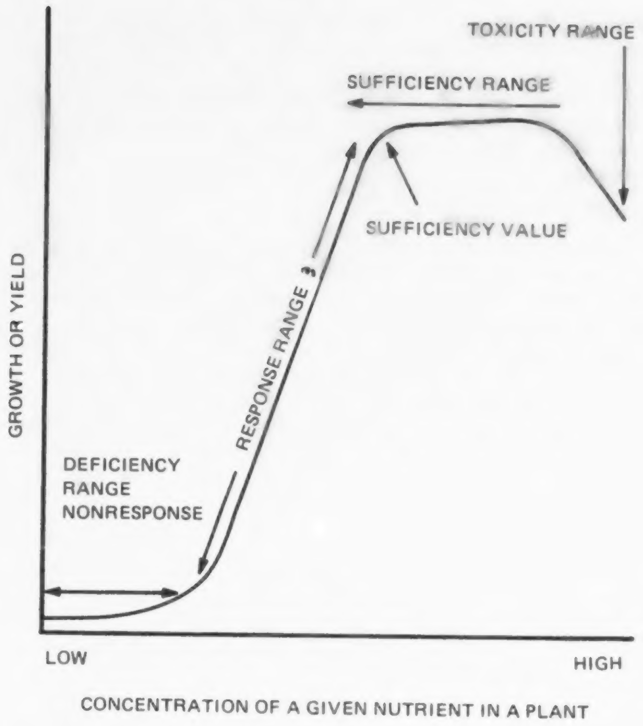
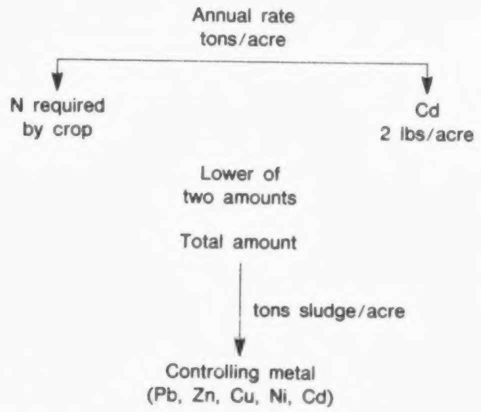


Figure 9–2.—Suggested terminology for the relationship between yield and the concentration of a given nutrient in a plant.

as the metals of primary concern.[22,23] The approach can be depicted as follows:



The plant available nitrogen from sludge is important in determining application rate. From the composition of a sludge, available nitrogen can be calculated:

$$\text{Available N} = NH_4^+ + NO_3^- + 20 \text{ percent of organic N.}$$

Data suggest that 15 to 20 percent of the organic nitrogen is converted to plant available forms the first year and 3 to 10 percent of the remaining organic nitrogen is released the second year (see table 9–13). Decreasing amounts of organic nitrogen are subsequently released each following year. Residual nitrogen from previous years of sludge application can be calculated from the amount of sludge added to soils. All inorganic nitrogen is assumed available for plant uptake. The reason for applying sludges at the nitrogen utilization rate of a crop is to minimize groundwater contamination due to nitrate leaching.

The amount of plant available N added to soils in sludge is influenced by the application method used. If sludges are applied and allowed to dry on the soil surface, from 20 to 70 percent of the NH_4-N applied can be lost to the atmosphere as NH_3. The exact proportion of NH_4-N lost through volatilization depends on soil, sludge and climatic conditions and is, therefore, difficult to predict. Based on laboratory[24] and field[25] studies, 50 percent volatilization losses of NH_4-N are assumed for surface applied sludges in the following design examples. No NH_3 volatilization losses are assumed for sludges applied to soil by injection or incorporation methods. As a result, the rate of sludge applied to satisfy the crop's N requirement will be greater for surface than incorporation application procedures.

Annual loading rates for cadmium (Cd) on soils are set at 2 lb/acre·year (2 kg/ha·year) for food chain crops;[9] however, this value can be regarded as provisional and may be revised based on ongoing and future research.[26] (Throughout this discussion, the units lbs/acre and kg/ha are used interchangeably because the uncertainties involved in establishing fertilizer recommendations, interpreting soil test data and setting heavy metal limits are greater than the 10 percent difference between lbs/acre and kg/ha. The actual conversion factor is 0.91 lbs/acre = 1 kg/ha.) This annual limit for Cd is based on Cd uptake by crops and the potential adverse effects on human health.

The life of a disposal site is based on the cumulative

Table 9–13.—Release of residual N in soils treated with sewage sludge[22]

Years after sludge application	Organic N content of sludge, percent						
	2.0	2.5	3.0	3.5	4.0	4.5	5.0
	Lb N released per ton sludge added[a]						
1	1.0	1.2	1.4	1.7	1.9	2.2	2.4
2	0.9	1.2	1.4	1.6	1.8	2.1	2.3
3	0.9	1.1	1.3	1.5	1.7	2.0	2.2

[a] 1.0 lb/ton = 0.5 Kg/metric ton.

amounts of lead (Pb), copper (Cu), nickel (Ni), zinc (Zn) and cadmium applied to the soil. These limits are designed to allow growth and use of crops at any future date. The limits for metal additions to soils are shown in table 9–14.[9] Phytotoxicity will be encountered for Zn, Cu and Ni before the concentrations of these metals in plants will adversely affect human or animal health.

Table 9–14.—Maximum amount of metal (lb/acre) suggested for agricultural soils treated with sewage sludge[a]

Metal	Soil cation exchange capacity (meq/100 g)[b]		
	<5	5 to 15	>15
	Maximum amount of metal (lb/acre)[c]		
Pb	500	1,000	2,000
Zn	250	500	1,000
Cu	125	250	500
Ni	50	100	200
Cd	5	10	20

[a] Developed by cooperative efforts of regional research projects NC-118 and W-124 and ARS, USDA and cited in ref. 9.

[b] Determined by the pH 7 ammonium acetate procedure.

[c] Lb/acre = 1.121 kg/ha.

Table 9–15.—Metal content of soils and crops[a]

Element	Conc. in soils		Conc. in plant diagnostic tissue	
	Common (mg/kg)	Range (mg/kg)	Normal (mg/kg)	Toxic[b] (mg/kg)
As	6	0.1–40	0.1–5	—
B	10	2–100	30–75	>75
Cd	0.06	0.01–7	0.2–0.8	—
Cr	100	5–3,000	0.2–1.0	—
Co	8	1–40	0.05–0.5	—
Cu	20	2–100	4–15	>20
Pb	10	2–200	0.1–10	—
Mn	850	100–4,000	15–100	—
Mo	2	0.2–5	1–100	—
Ni	40	10–1,000	1	>50
Se	0.5	0.1–2	0.02–2.0	50–100
V	100	20–500	0.1–10	>10
Zn	50	10–300	150200	>200

[a] Adapted from ref. 27.

[b] Toxicities listed do not apply to certain accumulator plant species.

Thus, the limits for Zn, Cu and Ni will prevent reduced plant yields due to phytotoxicity. The principal problem with Pb is the direct ingestion of soil particles by humans and animals. Essentially no plant uptake of Pb occurs. The Cd limit, as described, is not related to phytotoxicity but rather the accumulation of low concentrations of Cd in plants. Common metal levels in soils and crops are shown in table 9–15. The major factor for applying sludges to agricultural crops is that soil pH be maintained above 6.5, to minimize heavy metal uptake by plants.

The steps involved in calculating application rates can be summarized as follows:

Step 1. Obtain N requirement for the crop grown (see tables 9–9 to 9–12).

Step 2. Calculate tons of sludge needed to meet crop's N requirement.

a. Available N in sludge

$$\text{Percent organic N } (N_o) = (\text{percent total N}) - (\text{percent } NH_4\text{-N}) - (\text{percent } NO_3\text{-N})$$

Incorporated application[a]

$$\text{Lbs available N/ton} = (\text{percent } NH_4\text{-N} \times 20) + (\text{percent } NO_3\text{-N} \times 20) + (\text{percent } N_o \times 4)$$

Surface application[a]

$$\text{Lbs available N/ton} = (\text{percent } NH_4\text{-N} \times 10) + (\text{percent } NO_3\text{-N} \times 20) + (\text{percent } N_o \times 4)$$

(Note: The factor for NH_4-N is decreased by 50 percent to account for NH_3 volatilization)

b. Residual sludge N in soil

If the soil has received sludge in the past 3 years, calculate residual N from table 9–13.

c. Annual application rate

i) Tons sludge/acre

$$= \frac{\text{crop N requirement} - \text{residual N}}{\text{lb available N/ton sludge}}$$

---

[a] The conversion factor for NH_4- and NO_3-N is calculated from

$$\frac{\text{lbs N}}{\text{100 lbs sludge}} \times \frac{\text{2,000 lbs}}{\text{ton}} = 20$$

and for N_o (only 20 percent plant available)

$$\frac{\text{lbs } N_o}{\text{100 lbs sludge}} \times \frac{\text{2,000 lbs}}{\text{ton}} \times 0.2 = 4$$

If sludge is surface applied, this rate is increased due to N loss through NH_3 volatilization

ii) Tons sludge/acre[b] = $\frac{\text{2 lb Cd/acre}}{\text{ppm Cd} \times .002}$

iii) The lower of the two amounts is applied.

Step 3. Calculate total amount of sludge allowable.[c]

a. Obtain maximum amounts of Pb, Zn, Cu, Ni, and Cd allowed for CEC of the soil from table 9–14 in lbs/acre.

b. Calculate amount of sludge needed to exceed Pb, Zn, Cu, Ni, and Cd limits, using sludge analysis data.

Metal

Pb: Tons sludge/acre = $\frac{\text{lb Pb/acre}}{\text{ppm Pb} \times .002}$

Zn: Tons sludge/acre = $\frac{\text{lb Zn/acre}}{\text{ppm Zn} \times .002}$

Cu: Tons sludge/acre = $\frac{\text{lb Cu/acre}}{\text{ppm Cu} \times .002}$

Ni: Tons sludge/acre = $\frac{\text{lb Ni/acre}}{\text{ppm Ni} \times .002}$

Cd: Tons sludge/acre = $\frac{\text{lb Cd/acre}}{\text{ppm Cd} \times .002}$

Step 4. Calculate amount of P and K added in sludge.

Tons of sludge × percent P in sludge × 20 = lb of P added

Tons of sludge × percent K in sludge × 20 = lb of K added

Step 5. Calculate amount of P and K fertilizer needed.

[d](lb P recommended for crop) – (lb P in sludge)
= lb P fertilizer needed.

[d](lb K recommended for crop) – (lb K in sludge)
= lb K fertilizer needed.

Forested Lands

Forested sites offer special opportunities for the beneficial use of sludge through improving soil fertility and increasing plant growth.[9] Yet, the potential of forest lands as sites for utilizing sludge is often overlooked.[28] In contrast to many agricultural crops, forest products are generally not consumed by humans and thus, there is no reason to suspect forest products grown on sludge treated areas as constituting a human health hazard.[28] Furthermore, direct human contact in forests treated with sludge is minimal because of the low population density. However, not all features of forest land use are favorable. Public resistance may be encountered, accessibility may be poor, resident species, including wildlife, may be impacted, and special distribution systems may be necessary to overcome rugged and sloping terrain.[28]

Stand Properties and Nutrient Relationships

The ability of a forest system to utilize the nutrients applied in sewage sludge depends upon the maturity of the species present. The principles of nutrient accumulation in a forest stand are illustrated in figure 9–3. Nutrient accumulation is greatest during the early stages of growth. In a system approaching maturity, the majority of nutrients accumulated in previous years are merely recycled to maintain biomass. The time needed to achieve maximum nutrient accumulation depends on the tree species, but it is normally in terms of decades.

As with agronomic crops, the harvest of a forest stand removes the nutrients accumulated during growth. However, the amounts removed on an annual basin are significantly lower than for agronomic crops. The N and P removals by corn and selected tree species are shown in table 9–16. These data suggest that vegetative cover on forest soils is less important than in agricultural systems. Therefore, the use of sludge in forests must rely

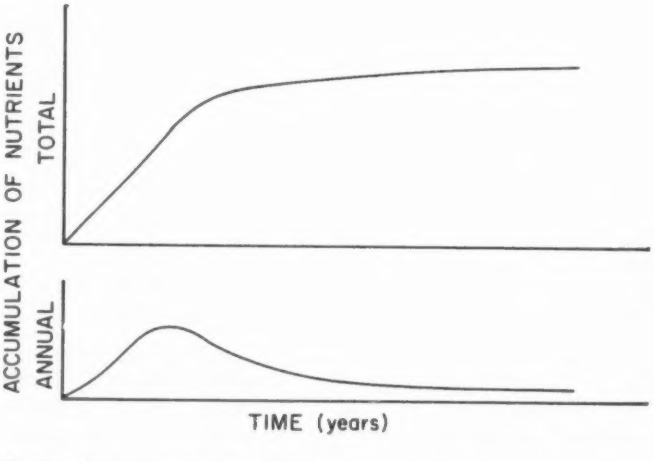


Figure 9–3.—Annual and total accumulation of nutrients for tree species.

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[b] The factor 0.002 is derived from:

$$\frac{1 \text{ lb}}{10^6 \text{ lbs}} \times \frac{2{,}000 \text{ lbs}}{\text{ton}} = 0.002$$

[c] Sludge metals should be expressed on a dry weight ppm (mg/kg) basis. The lowest value from the five calculations is the maximum tons of sludge per acre which can be applied.

[d] P and K recommendations based on soil tests for available P and K.

Table 9–16.—Nitrogen and phosphorus removal by corn and selected tree species[a]

Species	Nutrient removal			
	Cumulative (lbs/acre)		Average annual (lbs/acre·yr)	
	N	P	N	P
Corn				
Annual harvest (16 yrs)	1,600	288	100	18
Annual harvest (30 yrs)	3,000	540	100	18
Loblolly pine, age 16 yrs				
Whole tree (above ground)	227	27	14.2	1.7
Aspen, age 30 yrs				
Whole tree (above ground)	170	25	5.7	0.8
Deciduous				
Young			100	
Medium to mature			30–50	
Evergreen				
Young			60	
Medium to mature			20–30	

[a]Adapted from refs. 29 and 30

Table 9–17.—Response of tree species to effluent irrigation[28]

Response class to effluent		
Low	Intermediate	High
Slash pine	Tulip poplar	Cottonwood
Cherry Laural	Bald cypress	Sycamore
Arizona cypress	Saw-tooth oak	Green ash
Live oak	Red cedar	Black cherry
Holly	Laurel oak	Sweet gum
Hawthorne	Magnolia	Black locust
	Nuttall oak	Red bud
	Cherrybark oak	Catalpa
	Loblolly pine	Chinese elm

on soil processes in addition to plant uptake, to minimize the potential for NO_3^- leaching into groundwater.

The utilization of sludge in the establishment of a forest stand affords flexibility in choosing tree species which exhibit rapid growth rates and assimilate appreciable quantities of nutrients. In addition to nutrient uptake and growth considerations, the adaptability of a particular species to the climate (rainfall) and soil (pH, fertility, drainage) conditions must be evaluated. For example, pines favor acid soils whereas legumes (e.g., red bud, black locust, red cedar) require a near neutral pH. Smith and Evans[28] categorized the response of tree species of irrigation with municipal effluent (table 9–17). Similar results are anticipated when nutrients are applied in sludge. However, effluent irrigation will add appreciable quantities of water whereas a minimal amount will be added in sludges. Additional data are needed prior to recommending which species are most suited for sludge application sites.

For established forests, processes other than nutrient uptake by trees must be considered to prevent NO_3^- leaching. Even though available N has been added in excess of the N needed for tree growth, a minimal amount of NO_3^- leaching has been observed in field plot studies (D. H. Urie, personal communication). At increased rates of sludge amendments, NO_3^- movement to a 120-cm depth was encountered. Denitrification is the likely mechanism for depressed NO_3^- movement in forested systems. An additional consideration is the depressed rates of nitrification (i.e., $NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$) in forest soils which are typically acid. Since NH_4^+ can be bound by the exchange complex of soils, its downward movement will be limited.

Application Rates

Because of the minimal data on annual uptake of N by tree species, the approach adopted for calculating sludge application rates on forested lands is essentially the same as that used for slow rate wastewater irrigation systems.[31] The amount of sludge applied annually is based on: 1) an allowable NO_3^--N concentration in water percolating through the soil profile; 2) a fixed percentage of the N applied is lost through denitrification and 3) N uptake by the forest stand occurs.

The annual N loading rate is calculated from

$$L_n = U + D + 0.23\ W_pC_p$$

where

L_n = plant available N applied (lbs/acre·yr)
U = plant N uptake (lbs/acre·yr)
D = denitrification constant as a fraction of L_n added ($D = 0.2\ L_n$)
W_p = percolating water (in./yr)
C_p = percolate NO_3^--N concentration (mg/l)

The amount of percolating water can be either obtained from data sources or calculated as follows:

$$L_s + Pr = W_p + ET$$

where

L_s = sludge loading rate (in./yr)
Pr = precipitation (in./yr)
W_p = percolating water (in./yr)
ET = evapotranspiration (in./yr)

The relationship between L_n added and the percent solids and volume of sludge is

$$L_n = 22.7\ C_s L_s S$$

where

L_n = plant available N applied (lbs/acre·yr)
C_s = percent of available N in sludge on a dry weight basin (i.e., percent C_s = percent $N_o \times 0.2$ + percent N_i)
L_s = volume of sludge applied (in./yr)
S = percent solids in liquid sludge

Since sludges often contain 1 percent plant available N, the above equation indicates that a one inch application of a 4 percent solids sludge would add ~90 lbs (40.3 kg) plant available N per acre. In many cases, the amount of percolation will range from 5 to 10 times the volume of water added in sludge when liquid sludges are applied at a rate consistent with estimated plant uptake and denitrification of N.

As shown previously for agricultural crops, the contribution of residual N to the plant available N pool can be subtracted from the amount of N that can be applied each year. That is, L_n is corrected for residual N after performing the above calculations.

It must be emphasized that the above approach for calculating application rates for forest lands is based upon criteria for wastewater irrigation. If N uptake data are available for the species growing on a potential sludge utilization area, the calculations discussed previously for agronomic crops could be applied to forested lands and it would be the preferred method for obtaining application rates.

In contrast to agricultural systems, annual Cd loadings will not limit application rates because a nonfood chain crop is being grown. Although data are not available to substantiate the impact of cumulative metal additions in forest ecosystems, it may be advisable to follow the same criteria as used for agricultural lands (table 9–14). The adoption of metal limits would not only minimize any metal toxicities to trees but it would also allow growth of other crops on the soils if the area were cleared at a future date. In addition, the majority of forest soils are acid which would promote increased metal solubility. Based on limited data, it appears that the majority of metals added to forest soils in a surface application of sludge remain in the litter layer. To minimize the potential for metal movement, a soil pH near neutrality would be preferred but is not required for sludge application sites. In summary, the major differences between agricultural and forest soils are that forest soils can receive >2 lbs Cd/acre/yr (2.2 kg/ha/yr) and can have a soil pH ≤6.5.

Other Nonagricultural Uses

Stabilized sludge can also be used for the enhancement of parklands and highway median strips and for the reclamation of damaged or poor terrain. Since the use of sludge on these lands generally involves the growth of a crop (e.g., turf) or forest stand, design procedures and management considerations are generally similar to those previously considered.

FACILITIES DESIGN

Once the site has been chosen, the land application project may proceed to the design phase. This chapter covers detailed site investigations, preapplication treatment of sludge, transportation of sludge, application rates and methods, storage and types of crops.

Detailed Site Investigation

The site selection process described in "Site Selection" made use of available published sources of information, such as soil surveys and topographic maps for evaluating alternative sites. Onsite studies will also be necessary for a detailed evaluation of the soil resource. Soil mapping units of the published soil survey may include small areas of contrasting soils that could not be shown at the scale of a published survey, but that may influence the design and operation of the system or render a site unsuitable.

The site study should involve evaluation of representative soils to which sludge is to be applied.

The basic information obtained from soil analysis is useful for development of sludge application rates. The analyses required are:

1. Available phosphorus (P) and potassium (K).
2. Soil pH and lime requirement.
3. Cation exchange capacity (CEC).
4. Organic matter (only if plant available N is computed from organic matter).

Other types of soil data that may be obtained but are not essential to developing application rates include permeability, percolation, particle size distribution, bulk density, and conductivity. If soil analysis will be used to assess the accumulation of metals in soils, either extractable or total zinc, copper, lead, cadmium and nickel should be analyzed prior to initiation of sludge spreading. Information for soil sampling techniques can be obtained from SCS personnel or soil testing labs.

Preapplication Treatment

Preapplication treatment refers to sludge handling processes within the wastewater treatment plant. The basic objective of these processes is to prepare the sludge for ultimate disposal. For an existing treatment plant with its large capital investment, the composition of the sludge and handling processes will probably dictate or limit land utilization practices. The alternative is to adapt sludge processing systems to a land application system. This may include source pretreatment for control of heavy metals. Furthermore, the physical form of the sludge will influence its transport mode from treatment plant to application site.

Known waste-solids treatment processes usually are designed for reducing sludge volume and stabilization of solids. Several basic processes are used:

1. Conditioning.
2. Concentration or thickening.
3. Chemical or biological treatment (i.e., digestion, lagoons).
4. Dewatering.
5. Heat treatment.

Stabilization

There are a variety of stabilization methods currently in use. Their general effectiveness in attenuation of pathogens and odors is summarized in table 9–18. Anaerobic and aerobic digestion are most frequently used with heat and chemical treatment less prevalent. The recent EPA Technical Bulletin[9] suggests that stabilization methods other than anaerobic digestion may be equivalent to anaerobic digestion in reducing odor potential and volatile organics.

In the case of lime stabilization, absorption of CO_2 from the air can result in a pH reduction, subsequent regrowth of bacteria and the potential for odors. This destabilization may occur at the application site, if surface application methods are used. These problems are minimized by incorporation of lime stabilized sludges. Application of lime stabilized sludges will facilitate the maintenance of soil pH.

Table 9–18.—Attenuation effect of well conducted processes for stabilizing wastewater treatment sludges.

Process	Pathogens	Putrefaction potential	Odor
Lime treatment	Good	Fair	Good[a]
Anaerobic digestion	Fair	Good	Good
Aerobic digestion	Fair	Good	Good
Heavy chlorination	Good	Fair	Good
Pasteurization (70° C)	Excellent	Poor	Poor
Ionizing radiation	Excellent	Poor	Fair
Heat treatment (195° C)	Excellent	Poor[b]	Poor[b]
Composting (60° C)	Good	Good	Good
Long-term lagooning of digested sludge	Good	—	—
Heat drying	Excellent	Good[c]	Good[c]

[a] May only be temporary because of possible destabilization resulting from pH reduction.

[b] Good for filter cake.

[c] Anaerobic conditions in the soil after sludge is applied could cause odors.

Source: Reference 32.

Dewatering

Dewatering processes are used to reduce sludge volume and prepare the sludge for transport and disposal. The moisture content of sludges dewatered by vacuum filters and centrifuges is reduced to a range of 75 to 85 percent. At these concentrations the sludge can be carried in dump trucks and applied to the land with manure spreaders or incorporation equipment. The choice of dewatering systems does not affect the actual land application process, except for a consideration of the resultant moisture contents and chemical aids used. Vacuum filters often use lime for conditioning, and the resultant increase in pH can be valuable for agricultural application systems.

Transportation of Sludge

If sludge cannot be applied to a site immediately adjacent to the treatment plant, it must be hauled to another area. The principal methods of transport are tank truck and pipeline. Barge and rail have only limited applicability and are not widely used. The method of transportation chosen and its costs depend on a number of factors: (1) the nature, consistency, and quantity of sludge to be transported; (2) the distance to the site; (3) the availability and proximity of the transit modes to both the origin and destination; (4) the degree of flexibility required in the transportation mode; and (5) the estimated useful life of the ultimate disposal facility.

To minimize the danger of spills, odors, and dissemination of pathogens to the air, liquid sludges should be transported in closed vessels, such as tank trucks, covered or tank barges, or railroad tank cars. Stabilized, dewatered sludges can be transferred in open vessels, such as dump trucks or railroad gondolas, if they are covered with a tarpaulin.

Truck

Tank truck transport is the most common method of sludge haul. Flexibility and simplicity of operation are the key reasons for its popularity. Either liquid or dewatered sludge can be loaded into tank trucks or trailers directly from the digesters or storage tanks and hauled over most highways to any site or combination of sites. If conditions permit the sludge can be applied directly, eliminating the need for a distribution system at the site.

The tank trucks utilized for transporting liquid sewage sludges range in carrying capacity from about 600 to 7,500 gal (2.27 to 28.39 m^3). The smaller capacity trucks (600–3,500 gal. or 2.27 to 13.25 m^3) are usually straight tank trucks, while the larger are tractor-trailer rigs. The trucks, either gasoline or diesel fueled, seldom average more than 3 or 4 miles (4.80 or 6.4 km) to the gallon. A straight tank truck designed for hauling and spreading sludge can be purchased either as a single unit built to specifications, or the chassis, only, may be purchased for later tank installation. Vehicles of this type can have a "useful life" exceeding 10 years.

A wide range of tank truck configurations is possible. Some communities have converted water tanks and installed them on a truck chassis or even have carried them in a conventional dump truck, thus allowing dual use of the truck. A few communities have converted gasoline trucks, and one has even baffled and enclosed the box of a large dump truck in order to transport liquid sewage sludge.

Most of the tank trucks utilize gravity filling and emptying methods. Some trucks, however, are equipped with gasoline motor driven pumps for loading and spreading. The pumps can often supply the head of pressure required for short range spray irrigation. Keeping these sludge pumps primed can be a problem and constitute an additional energy requirement. As a general rule, tank trucks also include in-cab sludge release controls.[33]

Capital investment in a trucking operation is small but the operation may be expensive, especially for long hauls because of labor costs. If daily sludge volumes are small, one tank truck may be able to serve two or more wastewater treatment plants.

Pipeline

Use of pipelines for sludge transport is limited to liquid sludges. Applicability is further limited because the hydraulics of sludge flow vary with sludge characteristics. In general, viscosity, velocity and temperature are the principal factors influencing sludge flow. Viscosity, in turn, is determined by the solids content of the sludge and velocity is directly related to the flow rate and pipe diameter.

Sludge flow in pipelines is not the same as for water or other relatively uniform liquids. The usual engineering flow equations are not applicable to sludge flow unless the flow is turbulent. Design and operation of sludge pipelines is complicated by the varying nature of the sludge and the consequent unpredictable head losses.

A review of literature and practice gives the following conclusions on sludge flow in pipelines:[34]

1. The head loss in the pipeline varies directly with the viscosity of the sludge.
2. Increasing the velocity of sludge flow within the laminar range decreases the apparent viscosity. (Since sludges are a varying mixture of solids, they do not exhibit a true viscosity of more uniform liquids.)
3. Increasing the velocity of sludge flow in the turbulent range zone further decreases the apparent viscosity of sludge until the true viscosity is approached as a limit.
4. Reducing the size of coarse sludge particles reduces the viscosity of the sludge.
5. Effective grit removal is necessary for economical pumping of sludge in a pipeline.
6. The low velocities experienced in the laminar flow zone when raw primary sludge is pumped often result in deposition of grease on the inner periphery of the pipe wall.
7. Flow velocities in a turbulent flow region tend to prevent deposition of grease within the pipe.
8. Pumping anaerobically digested sludge results in lower head loss as a result of friction than pumping raw primary sludge of the same solids content (dry basis) and flow condition.
9. Maintaining the operating velocity in the lower portion of the turbulent flow zone results in maximum economy for pumping sludge through a long pipeline.
10. Little or no grease deposition within the pipeline has been observed over periods of many years when low-solids-content activated sludge is pumped.
11. Pipeline materials and linings influence pipeline head losses as a result of differing friction flow factors. Some pipeline materials and linings such as glass lining, cement lining, and fiberglass-reinforced epoxy pipe resist the adherence of greases more readily than other materials such as cast iron and steel.

The critical factor in sludge piping is head loss. Head loss (and energy requirement) is a function of pipe diameter, pipe material (roughness) and velocity of flow. In the laminar flow range, head losses can be prohibitively high.[35] Furthermore the low velocities could result in accumulation of grease and deposition of grit, further increasing pipe roughness. To avoid these problems, a turbulent flow velocity of at least 4 to 6 feet per second (1.2 to 1.8 m/s) should be maintained.

Energy requirements are also inversely proportional to the fifth power of the pipe diameter (Hazen-Williams formula). Consequently, energy costs for sludge flow in small pipelines at high velocities for long distances can be very high.

For turbulent flow, head losses in sludge pipes need to be adjusted upward from those computed based on water. One reference suggests that the "C" factor in the Hazen-Williams formula should be decreased as moisture content decreases, as illustrated in figure 9–4. An optimum solids content (in terms of economics of pumping) appears to be about 5 percent for turbulent flows in 10-inch (25.4 cm) diameter or smaller pipes. Solids concentrations above 5 percent are believed to result in flow regimes within the plastic flow range, hence very difficult to produce a turbulent flow condition. In larger pipes, the optimum solids content may be higher.[37]

Pipelines require a larger initial capital investment than trucks, but operating costs are considerably lower than labor-intensive trucking. Once the pipeline is constructed, the route is fixed, restricting pipelines to long term application sites. However, pipeline construction costs exhibit economies of scale with respect to flow. Thus, for a given distance, pipelines may be less expensive than trucks for sludge transportation.

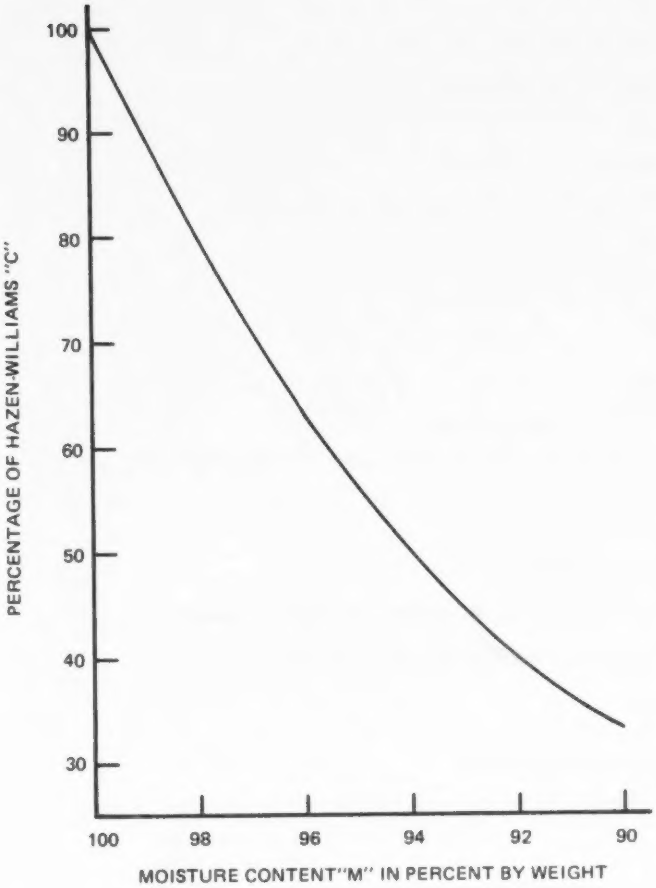

Figure 9–4.--Variation in headloss coefficients for turbulent flow of raw sludge.[36]

Barge

Barge transport presents limitations for land application, because other modes must be used to transfer the sludge from the barge to the disposal site. Additional capital investment for loading and unloading facilities would therefore be required. Many different barge sizes and types are available for transporting sludge. Generally, double-hulled vessels should be used to reduce the possibility of spills in congested harbor areas. Barges may be either towed or self-propelled but will usually require pumped discharges.

Railroad

Rail transport is not a widely used alternative in the United States. It provides the option of transporting sludges of any consistency. Like pipeline and barge transport, however, rail may require substantial fixed capital investment. In addition, availability of suitable cars may be a problem. Using leased or shipper-owner cars would be the best way to assure car availability.[38]

Summary Evaluation

Each mode is evaluated and rated in table 9–19 in terms of reliability, staffing needed, and environmental impact. Costs are considered in more detail in "Costs." In determining which transportation mode will be selected to convey sludge from the plant to the site, sludge characteristics, elevation differences, distance, and sludge volumes must be considered.

Application Methods

A variety of application methods is summarized in tables 9–20 to 9–22 and discussed below.

Liquid Sludge

Application of sludge in the liquid state is desirable because of its simplicity. Dewatering processes are not required and inexpensive liquid transfer systems can be used. Four common liquid application systems are described in the following paragraphs.

Tank Truck Spreading

A common method of liquid sludge application is direct spreading by tank trucks (see figure 9–5), tractors and farm tank wagons having capacities of 500 to 3,000 gal (1.9–11.4 m^3). Sludge is spread from a manifold on the rear of the truck or wagon as it is driven across the field. Application rates can be controlled either by valving the manifold or by varying the speed of the truck. One modification of the basic process is to mount a spray apparatus on the truck so that a wider application area can be covered by each pass. The spray system can be refined so that larger tank trucks can operate from a network of roads at the application site.

The principal advantages of a tank truck system are low capital investment and ease of operation. The system is also flexible in that a variety of application sites can be served, such as pastures, golf courses, farmland, and athletic fields.

Disadvantages include wet-weather problems and the high operating cost of the sludge haul. Tank trucks are not able to enter sites when the ground is soft. Consequently, storage or wet-weather handling alternatives must be available. Special flotation tires used on the trucks can partially control this problem.[41] Repeated tank truck traffic may also reduce crop yields. This is primarily the result of damage to soil structure (higher bulk density, reduced infiltration) from the trucks rather than the sludge itself.[42]

Table 9–19.—Evaluation of sludge transport modes

Rating criteria	Transport mode alternatives					
	Truck-barge pipe	Pipe-barge pipe	Barge-pipe	Railroad	Truck	Pipeline
Reliability and complexity[a]	2	2	3	1	1	3
Staffing skills[b]	3	3	3	2	1	3
Staff attention (time)[c]	4	3	4	1	3	2
Applicability, flexibility[d]	3	3	3	2	1	3
Energy used[e]	7	3	5	2	8	6
Cost						
Capital investment	High	High	High	—	Low	High
Operation maintenance, labor	High	Moderate	Moderate	—	Fairly high	Low
Overall[f]	—	—		Generally high[g]	—	—

[a] 1 = most reliable, least complex; 3 = least reliable, most complex.
[b] 1 = least skills; 3 = highest skills.
[c] Attention time increases with magnitude of number.
[d] 1 = wide applicability (all types of sludges); 3 = limited applicability, relatively inflexible.
[e] 1 = lowest; 8 = highest.
[f] Overall costs are a function of sludge quantities and properties (percent solids), distance transported, and need for special storage, loading and unloading equipment.
[g] Rail costs would generally be in the form of freight charges; costs could be lower for large volumes of sludge.
Source: Adapted from ref. 39.

Table 9–20.—Surface application method and equipment for liquid sludges[40]

Method	Characteristics	Topographical and seasonal suitability
Irrigation		
Spray (sprinkler)	Large orifice required on nozzle; large power and lower labor requirement; wide selection of commercial equipment available; sludge must be flushed from pipes when irrigation completed.	Can be used on sloping land; can be used year-round if the pipe is drained in winter; not suitable for application to some crops during growing season; odor (aerosol) nuisance may occur.
Ridge and furrow	Land preparation needed; lower power requirements than spray.	Between 0.5 and 1.5 percent slope depending on percent solids; can be used between rows of crops.
Overland	Used on sloping ground with vegetation with no runoff permitted; suitable for emergency operation; difficult to get uniform aerial application.	Can be applied from ridge roads.
Tank truck	Capacity 500 to more than 2,000 gallons; larger volume trucks will require flotation tires; can use with temporary irrigation set-up; with pump discharge can spray from roadway onto field.	Tillable land; not usable with row crops or on soft ground.
Farm tank wagon	Capacity 500 to 3,000 gallons; larger volume will require flotation tires; can use with temporary irrigation set-up; with pump discharge can spray from roadway onto field.	Tillable land; not usable with row crops or on soft ground.

Spraying

Wastewater sludge can be applied to the land by either fixed or portable irrigation systems that have been designed to handle solids without clogging. This method may be useful for application on agricultural and forested lands.

The advantages of spraying include reduced operating labor, less land preparation, and a wide selection of commercially available equipment. Operator attention is

Table 9–21.—Subsurface application methods and equipment for liquid sludges[40]

Method	Characteristics	Topographical and seasonal suitability
Flexible irrigation hose with plow furrow or disc cover	Use with pipeline or tank truck with pressure discharge; hose connected to manifold discharge on plow or disc.	Tillable land; not usable on wet or frozen ground.
Tank truck with plow furrow cover	500-gallon commercial equipment available; sludge discharged in furrow ahead of plow mounted on rear of 4-wheel-drive truck.	Tillable land; not usable on wet or frozen ground.
Farm tank wagon and tractor		
Plow furrow cover	Sludge discharged into furrow ahead of plow mounted on tank trailer—application of 170 to 225 wet tons/acre; or sludge spread in narrow band on ground surface and immediately plowed under—application of 50 to 125 wet tons/acre.	Tillable land; not usable on wet or frozen ground.
Subsurface injection ...	Sludge discharged into channel opened by a tillable tool mounted on tank trailer; application rate 25 to 50 tons/acre; vehicles should not traverse injected area for several days.	Tillable land; not usable on wet or frozen ground.

Table 9–22.—Methods and equipment for application of semisolid and solid sludges[40]

Method	Characteristics
Spreading.....................	Truck-mounted or tractor-powered box spreader (commercially available); sludge spread evenly on ground; application rate controlled by over-the-ground speed; can be incorporated by discing or plowing.
Piles or windrows	Normally hauled by dump truck; spreading and leveling by bulldozer or grader needed to give uniform application; 4 to 6 inch layer can be incorporated by plowing.
Reslurry and handle as in tables 9–20 and 9–21.	Suitable for long hauls by rail transportation.

required to set portable sprinkler systems but fixed units can be highly automated. Sprinklers can operate satisfactorily on land too rough or wet for tank trucks or injection equipment. The method can be used throughout the growing season.

Disadvantages include power costs of high pressure pumps, contact of sludge with all parts of the crop, possible foliage damage to sensitive crops, and the potential for aerosol pollution from entrained pathogens. The sludge-crop contact problems will also limit the types of crops that can be grown. For forested systems, water under high pressure may physically damage trees while, at low pressures, the dispersal of sludge may be impaired by trees. Perforated pipe located above the shrub layer may be most effective in forested systems.

Incorporation

The principle of incorporation is to cut a furrow, deliver sludge into the furrow, and cover the sludge, all in one operation. Modifications include an injection system in which the sludge is injected beneath the soil surface (see figure 9–6), or use of a shallow disc. The advantage of incorporation is the immediate mixture of sludge and soil. Potential odor and vector problems from ponding sludge are eliminated and surface runoff is controlled. Incorporation procedures are favored because less nitrogen is lost from the soil through ammonia volatilization.

The principal disadvantages of incorporation are its seasonal limitations and handling procedures. Application can be made only prior to the growing season or on noncultivated land, therefore, it may be difficult to sequence sites throughout the year. Further, equipment has limitations for use on wet or frozen ground.

Ridge and Furrow

Ridge and furrow sludge application is comparable to that used in agricultural systems (see figure 9–7). Sludge flows in furrows between row crops, simultaneously irrigating and fertilizing the soil. Furrow slope is the key factor in the success of ridge and furrow application. The effect of furrow slope on sludge application is summarized in table 9–23 for a study in the Sacramento, California, area.

Advantages of ridge and furrow irrigation include simplicity, flexibility, and lower energy requirements than irrigation. The disadvantages include the settling of solids at the heads of furrows and the need for a well-prepared site, with proper gradients. Ponding of sludge in the furrows, which can result in odor problems, is also possible.

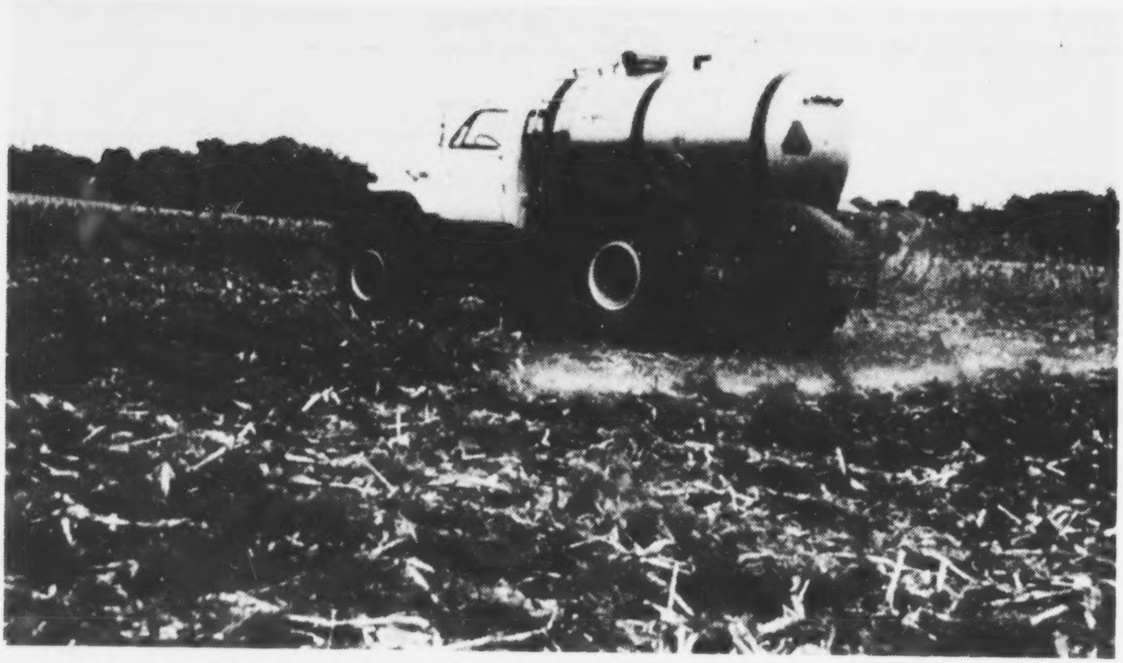

Figure 9–5.—A flotation tire tank truck spray applying liquid sludge.

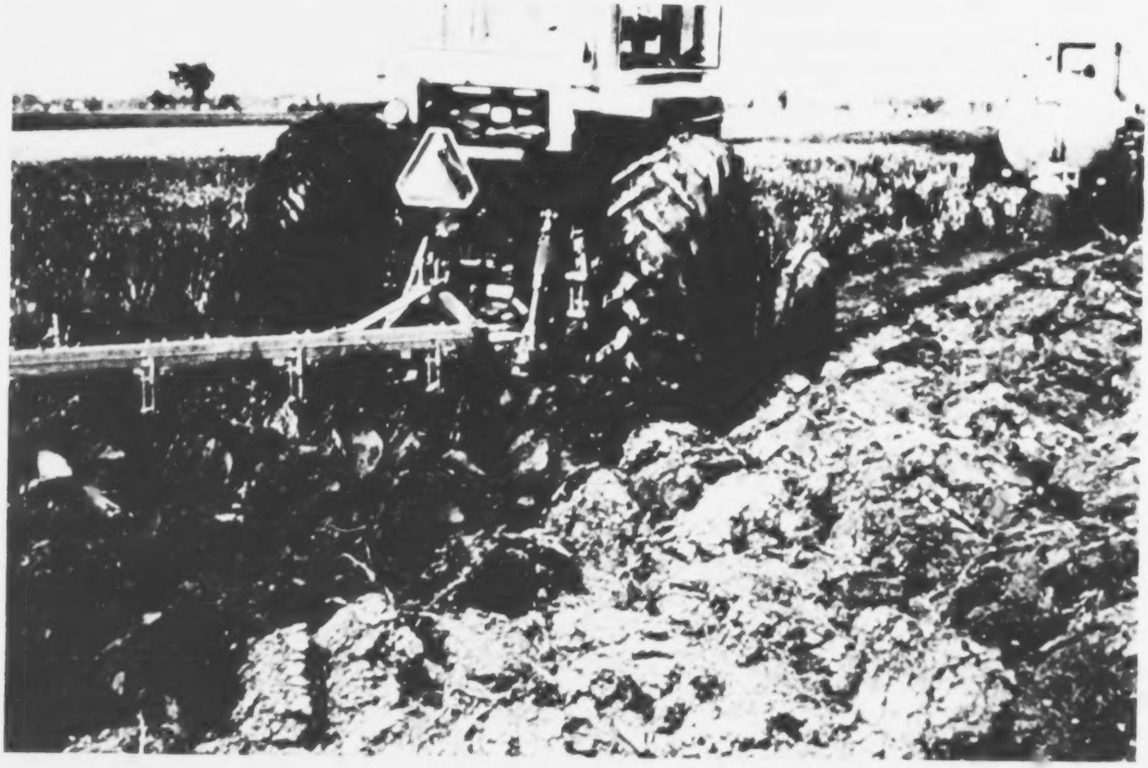

Figure 9–6.—Sludge incorporation into the soil.

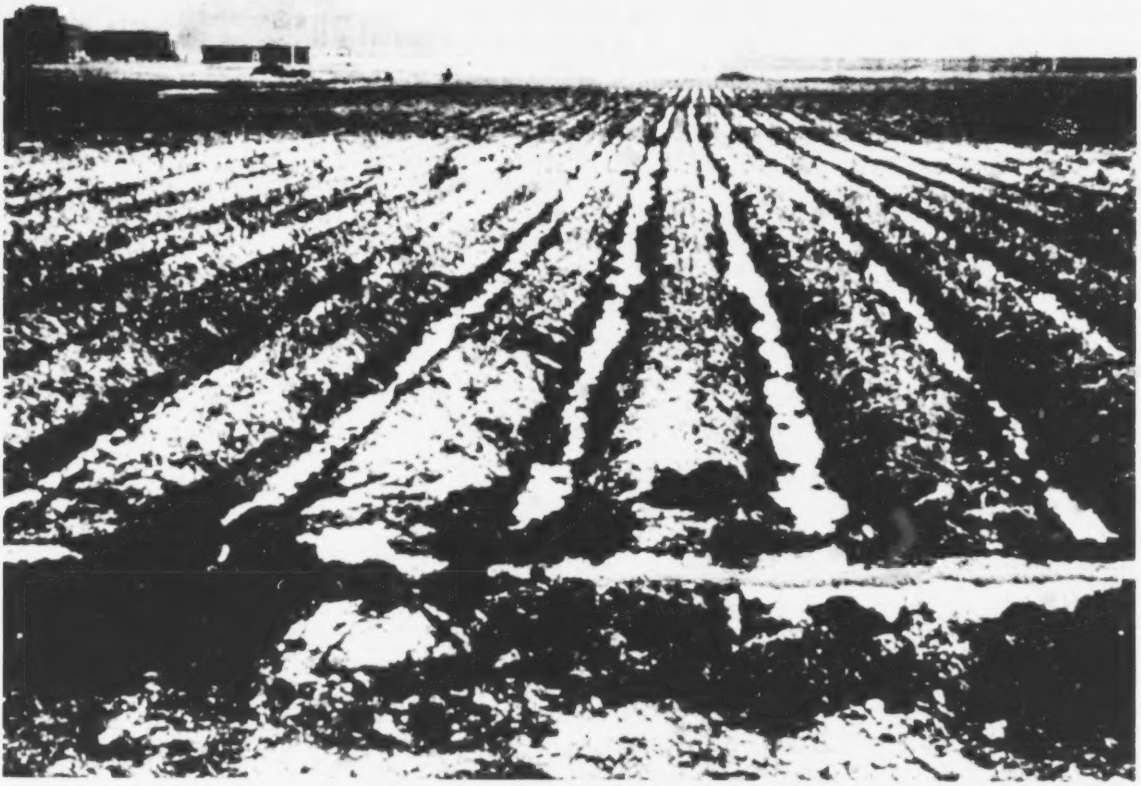

Figure 9–7.—A ridge and furrow system.

Table 9–23.—Furrow slope evaluation[44]

Slope[a] (percent)	Percent solids[b]	Observations[c]
0.1.........	3.1	Sludge ponded or flowed very slowly. On slopes this flat slight variations in grade cause ponding. Generally unsatisfactory.
.2.........	3.1	No ponding, sludge flowed slow. Minimum grade for 3 percent solids. Would be too flat for 5 percent solids.
.3.........	3.1	Sludge flowed evenly at a moderate rate. Excellent slope for 3 percent solids.
.4–.5	2.7	Sludge flowed evenly at a moderate rate. If not covered when furrows was full all the sludge would flow to the low end and pond. Excellent slope for sludge with 5 percent solids.

[a] 0.1 percent equals 0.1 foot of fall per 100 feet of run.

[b] Percent solids expressed determined in a dry weight basis.

[c] All observations are based on 12 in. deep furrows. Deeper furrows would permit the use of flatter slopes.

Dewatered Sludge

Application of dewatered sludge is similar to application of solid or semisolid fertilizers, lime, or animal manure. Spreading can be done with bulldozers, loaders, graders, or box spreaders and then plowed or disced in. Trench incorporation is also useful when reclaiming land of marginal agricultural value.[43]

The principal advantage of using dewatered sludge is that conventional equipment for application of fertilizer, lime, etc., and for tillage can be used. Most farmers already own tractors, discs, plows, or trucks, and would not need to purchase special equipment. Another advantage is that dewatered sludge usually may be applied at higher rates than liquid sludge since concentration of critical constituents (notably nitrogen) is reduced in the dewatering process. The application process for dewatered sludge is similar to liquid sludge and involves a two-step operation—spreading followed by plowing or discing.

Back-Up Systems

Site design should include contingency plans in case of equipment breakdowns or inclement weather. Back-up equipment should always be available. Storage (see below) can provide short-term protection against inability to spread and an alternate disposal site or method should be designated for long-term problems.

Storage

Storage facilities are required to hold sludge during periods of inclement weather, equipment breakdown, frozen or snow-covered ground, or when access would damage the field or plants. Storage capacity can be provided by digesters, tanks, lagoons, drying beds, or stockpiles. Volume requirements will be dependent on individual systems and climate. The minimum storage volume would consist of excess capacity in the digesters while maximum storage volume would be that required for an extended wet-weather or cold weather season.

Many sewage treatment plants which utilize landspreading do not have separate retention capacity for containing the sludge prior to landspreading. Instead, they utilize portions of the digester volume for storage. Where possible, a secondary unheated digester may provide the required short-term storage capacity. In anticipation of periods when sludge cannot be applied to the land, digester withdrawals proceed at an accelerated rate to ensure the availability of retention volume until the landspreading operation can be resumed. The fact that digesters often serve as retention vessels can lead to potential problems at the landspreading site if the sludge withdrawn for landspreading is insufficiently stabilized and contains high counts of pathogenic microorganisms.

Some sewage treatment plants operate sludge lagoons for either routine sludge dewatering or as holding reservoirs when landspreading practices are temporarily interrupted due to adverse weather conditions and/or unanticipated equipment failure. Other plant appurtenances such as the sludge wells associated with decommissioned or seasonally operated vacuum filter dewatering equipment are often utilized to provide retention volume. In rare cases, a cell of a secondary aerated system may be utilized for the retention of liquid sludges prior to transport to the landspreading site.

Extended use of vented sludge wells as holding reservoirs allows time for additional stabilization. However, open retention vessels may create odors if the sludges have not been sufficiently stabilized. Some plant operators have had difficulty in resuspending sludges which have been retained in lagoons, wells, and secondary unheated digesters due to long-term gravity separation of the solid and liquid phases.[45] Storage areas can also provide for disinfection. However, some organisms can survive extended storage so that disinfection is not complete.[46]

MANAGEMENT AND MONITORING

Management

The design and management of each site will be unique and require the coordinated efforts of the land owner, the treatment plant operator, political officials, and engineers. While no one management technique can be recommended for all situations, there are a few general principles that can always be followed:

1. Minimize the impact on soils, groundwaters, surface waters, crops and air.
2. Control access to the site.
3. Schedule the operation.
4. Create favorable public impressions of the project.

Site Access Control

Although selected and designed to minimize environmental hazards, it is wise to restrict site access to authorized personnel. This is more important for sites dedicated to sludge utilization than for privately owned farmland where lower rates of sludge application are used.

Access roads must be maintained in an all-weather condition. As a minimum, gravel should be the minimum surfacing.

Scheduling

Timing of sludge applications need to correspond to farming operations and are influenced by crop, climate and soil properties.

As mentioned in "Preliminary Planning," sludge cannot be applied during periods of inclement weather and/or when the ground is frozen or covered with snow. Soil moisture is the key parameter affecting timing of sludge applications. Applications to wet soils during or immediately following heavy rainfall could result in compaction and reduced crop yields; muddy soils would also make vehicle operation difficult. Application to frozen or snow-covered ground may result in excessive runoff into adjacent streams. In addition, sludge applications must be scheduled around the tillage, planting and harvesting operations for the crops grown.

At very high application rates sludges can retard seed germination and early plant growth. The retardation is thought to be caused by a high concentration of soluble salts and/or high ammonia contents. These problems can be minimized by (1) reducing the application rate; (2) applying the sludge 2 to 3 weeks before planting; (3) mixing of the sludge in the tilled soil layer, or (4) irrigating prior to planting. In the humid regions of the United States, the problem will be potentially less severe than in the more arid nonirrigated regions.

Sludges can be applied to forage crops during the season if applied prior to spring growth, after dormancy, or immediately after cutting and before significant new growth has begun.

Sewage sludge applied to the surface of poorly drained soil and not immediately incorporated can be transported in runoff waters and result in contaminated surface waters. The potential danger of runoff increases greatly on sloping land in regions of high rainfall and can be severe if an intense rain occurs soon after liquid sludge is spread on sloping land. Diversion or earthen barriers may be necessary to contain runoff temporarily, and prevent sludge from reaching water courses. In addition, erosion control practices such as grassed waterways, terraces, and strip cropping are useful to decrease runoff from sludge amended soils. Regardless of land use, runoff can be minimized by lowering sludge application rates, using split applications, and by incorporating sludge rather than surface spreading.

Favorable Impressions

As discussed in "Preliminary Planning," knowledge of landspreading operations was directly related to positive attitude toward landspreading. A well-run operation would help to sustain these attitudes.

The entire project should be professionally operated. The staff should consist of personnel having working knowledge of farming, wastewater treatment, and sludge handling. Any complaints or questions from the public should be dealt with promptly and courteously.

Presence of objectionable odors could result in an unfavorable public impression of the concept. To minimize odors, the following operational procedures can be used:

1. Injection of unstable wastes.
2. Incorporation of all sludge as soon as possible after delivery to site.
3. Daily (or more frequently, if necessary) cleaning of trucks, tanks, and other equipment.

Monitoring

Any sludge application site must have a monitoring program for observing and evaluating systems performance. Sludge composition, groundwater quality, soil properties, and plant composition would be monitored in an optimum sampling program.

Periodic Sludge Analyses

Sludge analysis confirms, on a regular basis, that the waste is acceptable and provides a record of nutrient and metal additions to soils. Sampling frequency depends on sludge characteristics and sludge variability.[47] For example, a treatment plant processing large amounts of industrial wastes at irregular intervals may need continuous monitoring, whereas a system processing largely domestic wastes may need only intermittent sludge monitoring.

Recommended analysis and suggested analytical methods are shown in table 9–24. Since the solids content of sludges varies from batch to batch, all composition data must be expressed on an oven-dry solids basis.

The following elements may be of concern in special instances, but for most sewage sludges which are encountered these elements will not influence the rate of application of sludge to land: selenium, cobalt, chromium, arsenic, boron, iron, aluminum, mercury, silver, barium, sulfur, calcium, magnesium, sodium, molybdenum, inorganic carbon, and organic carbon. With the exception of boron, sulfur, and carbon, all analyses listed above can be accomplished with atomic absorption spectrophotometry. The elements arsenic, selenium, boron, chromium, and mercury are of greatest importance in industrial wastes; however, some municipal sludges may contain elevated levels if these metals of industrial wastes are added to the sewage system.

Table 9–24.—Methods for sludge analysis[26]

Parameter	Suggested method
Percent solids	Drying at 105° C for 16 hrs.
Total N (nitrogen)	Micro-Kjeldahl and S.D.[a]
NH_4^+-N (ammonium)	Extraction with potassium chloride and S.D.[a]
NO_3^--N (nitrate)	Extraction with potassium chloride and S.D.[a] after reduction
Total P (phosphorus)	Nitric acid-perchloric acid digestion and colorimetry
Total K (potassium)	Nitric acid-perchloric acid digestion and flame photometry
Copper (Cu), zinc (Zn), nickel (Ni), Lead (Pb), and cadmium (Cd).	Nitric acid-perchloric acid digestion and atomic absorption[b]
Stable organics[c]	Variable

[a] S.D., steam distillation and titration of distillate with standard sulfuric acid. Colorimetric procedures can be used for N species.

[b] Background correction (e.g., deuterium or hydrogen lamp) may be needed for cadmium and nickel.

[c] Optional and site specific.

Site Analyses

Monitoring requirements for sites are a function of the sludge application rate. Sludges applied at a rate equal to crop nutrient requirements can be considered as fertilizers; therefore, no special monitoring is necessary. This is usually the situation where sludge is given or sold to a farmer and then applied by the farmer and/or treatment plant on his land. Periodic soil testing should be conducted, including soil pH. It is recommended, that lime be added if soil pH decreases below 6.5.

When sludge is applied at rates exceeding recommended plant nutrient requirements or heavy metal limits, a special monitoring program will be required. This situation often occurs when sludge is applied to a municipally owned or leased site.

Soils

The initial monitoring of soils provides a reference datum specifying original conditions as well as necessary or tolerable sludge constituent additions which can be made. Subsequent soil analyses document contaminant buildups, efficacy of plant uptake and removals, evenness of sludge application and other environmental impacts. Soil analysis also allows calculation of sludge loading rates and provides estimates of remaining site life.

Irrespective of the constituent monitored, valid soil sampling techniques are essential. Soil testing laboratories describe procedures that can be used for obtaining soil samples. The sampling design should take into account changes in soil type as the area is traversed as well as within unit variability. Standardized analytical procedures for sludge amended soils have not been established but analytical procedures used for agricultural or forested soils are generally satisfactory. Interference problems may, however, negate the use of some analytical procedures.

The type of analysis is dependent on system objectives, although it is generally agreed that heavy metal and nitrate analysis should be performed for both agricultural and nonagricultural systems. The vertical distribution of these parameters in the soil profile would provide information on constituent mobility and potential for groundwater contamination. Additional analyses (P, K, pH, CEC, organic matter) would be required to provide information for fertilizer recommendations and site management (e.g., liming to adjust pH).

The movement of nitrates into groundwater may require monitoring in some instances. If sludge applications are applied in accord with the nitrogen requirement of the crops grown, nitrate leaching will be minimized. One approach to monitoring involves obtaining soil cores to a depth of 3 to 5 feet (0.9 to 1.5 m) at the end of the growing season and analyzing each 1 foot increment for ammonium (NH_4^+) and nitrates (NO_3^-). Suction lysimeters can also be used to obtain samples of the soil solution at a 3 to 5 foot (0.9 to 1.5 m) depth but this procedure has practical limitations.

Groundwater and Runoff

Most states have laws and regulations governing the quality of surface and groundwater which must be considered when designing a monitoring program. Sludge application to land is not the same as landfill, so regulations for groundwater quality from landfills do not apply to sludge applications.

Monitoring wells must be designed and located to meet the specific geologic and hydrologic conditions at each site. Furthermore, casing materials and drilling needs should be chosen to minimize potential, construction-related contamination problems.

Consideration should be given to the following:

1. Geological soil and rock formations existing at the specific site.
2. Depth to an impervious layer.
3. Direction of flow of groundwater and anticipated rate of movement.
4. Depth of seasonal high water table and an indication of seasonal variations in groundwater depth and direction of movement.
5. Nature, extent, and consequences of mounding of groundwater which can be anticipated to occur above the naturally occurring water table.
6. Location of nearby streams and swamps.
7. Potable and nonpotable water supply wells.
8. Other data as appropriate.[16]

If possible, existing background data should be obtained from wells in the same aquifer both beyond and within the anticipated area of influence of the land application system. Wells with the longest history of data are preferable. Monitoring of background wells should continue after the system is in operation to provide a basis for comparison.

In addition to background sampling, groundwater samples should be taken at perimeter points in each direction of groundwater movement from the site. In locating the sampling wells, consideration must be given to the position of the groundwater flow lines resulting from the application. Perimeter wells should be located sufficiently deep to intersect flow lines emanating from below the application area but not so deep as to prolong response times.

Water level measurements should be accurate to 0.01 feet or 1/8 inch (0.3 cm) and referenced to a permanent reference point, preferably U.S. Geological Survey datum. Measurements should be made under static water level conditions prior to pumping for sample collection. All monitoring wells should be securely capped and locked when not in use to avoid contamination.

Again, sampling frequency is dependent on system objectives, sampling variability and analytical costs. As a general rule, samples should be collected monthly during the first 2 years of operation. After the accumulation of a minimum of 2 years of groundwater monitoring information, modification of the sampling frequency may be considered. The following sampling procedures should be employed:

1. A measured amount of water equal to or greater than three times the amount of water in the well and/or gravel pack should be exhausted from the well before taking a sample for analysis. In the case of very low permeability soils, the well may have to be exhausted and allowed to refill before a sample is collected.
2. Pumping equipment should be thoroughly rinsed before use in each monitoring well.
3. Water pumped from each monitoring well should be discharged to the ground surface away from the wells to avoid recycling of flow in high permeability soil areas.
4. Samples must be collected, stored, and transported to the laboratory in a manner to avoid contamination or interference with subsequent analyses.

Water samples collected from sludge application sites should be analyzed for the following:

1. Chloride.
2. Conductivity.
3. pH.
4. Total hardness.
5. Alkalinity.
6. Total nitrogen.

7. Ammonia nitrogen.
8. Nitrate nitrogen.
9. Total phosphorus.
10. Methylene blue active substances.
11. Total organic carbon.
12. Heavy metals or toxic substances where applicable.

Vegetation

Plant tissue composition is a sensitive and meaningful indicator of impacts, provides useful information on plant nutrient deficiencies and toxicities, and indicates potential health hazards in food-chain crops. However, the validity and usefulness of a chemical analysis depends on a realistic approach to the problem of obtaining a reliable sample. To obtain reproducible data on plant composition, the age and part of the plant sampled must be specified because composition changes throughout the growing season.

The basic principles underlying plant tissue sampling are common to both forestry and agricultural species, but specific methodologies are unique to both practices. Forestry investigations in the Pacific Northwest recommend the following foliar sampling procedures.[48]

1. Sample conifer foliage during the dormant season.
2. Sample deciduous leaves at maturity.
3. Sample both dominant and codominant trees.
4. Sample upper portion of the crown for foliage samples.
5. Sample current year foliage.
6. Do not sample foliage or twigs bearing cones.

A summary of sampling techniques for agricultural crops is presented in table 9–25. Although the use of vegetable crops is not recommended on soils treated with sludge, diagnostic tissues for these crops are also presented. From the standpoint of metal impact on the human food chain, sampling the mature grain or forage is the preferred method of monitoring. Plant analyses can be performed using methods similar to those described previously for sludge. The major emphasis is placed on analysis of zinc, copper, nickel, cadmium, and lead. In some cases, analysis of the diagnostic tissue may allow prediction of the eventual metal concentration in the grain; however, insufficient data is presently available for most crops to develop general predictive relationships. The U.S. FDA has not set limits for allowable heavy metal concentrations in plant tissues consumed by humans or animals.

COSTS

Generalized cost curves for land application of sludge, including preapplication treatment and transport, are pre-

Table 9–25.—Suggested procedures for sampling diagnostic tissue of crops[19]

Crop	Stage of growth[a]	Plant part sampled	Number plants/ sample
Corn	Seedling	All the above ground portion.	20–30
	Prior to tasselling	Entire leaf fully developed below whorl	15–25
	From tasseling to silking	Entire leaf at the ear node (or immediately above or below).	15–25
Soybeans and other beans	Seedling	All the above ground portion.	20–30
	Prior to or during early flowering	Two or three fully developed leaves at top of plant.	20–30
Small grains	Seedling	All the above ground portion.	50–100
	Prior to heading	The 4 uppermost leaves.	50–100
Hay, pasture or forage grasses	Prior to seed emergence	The 4 uppermost leaf blades.	40–50
Alfalfa, clover and other legumes	Prior to or at 1/10 bloom	Mature leaf blades taken about 1/3 of the way down the plant.	40–50
Sorghum-milo	Prior to or at heading	Second leaf from top of plant	15–25
Cotton	Prior to or at 1st bloom, or at 1st square	Youngest fully mature leaves on main stem.	30–40
Potato	Prior to or during early bloom	3d to 6th leaf from growing tip	20–30
Head crops (e.g., cabbage)	Prior to heading	1st mature leaves from center of whorl.	10–20
Tomato	Prior to or during early bloom stage	3d or 4th leaf from growth tip.	10–20
Beans	Seedling	All the above ground portion.	20–30
	Prior to or during initial flowering	2 or 3 fully developed leaves at the top of plant.	20–30
Root crops	Prior to root or bulb enlargement	Center mature leaves.	20–30
Celery	Mid-growth (12–15" tall)	Petiole of youngest mature leaf.	15–30
Leaf crops	Mid-growth (12–15" tall)	Youngest mature leaf.	35–55
Peas	Prior to or during initial flowering	Leaves from 3d node down from top of plant.	30–60
Melons	Prior to fruit set	Mature leaves at base of plant on main stem.	20–30

[a] Seedling stage signifies plants less than 12 inches tall.

sented. The curves should be used only for preliminary work since actual costs vary considerably with local conditions. *Use of these curves for computing specific project costs is not recommended.*

Scope

Two sets of curves are presented: one set for sludge transport and one set for application. Transportation costs are presented as annual costs vs. distance to the application site for treatment plant capacities of 4, 10, 40, and 80 Mgal/d (0.18, 0.44, 1.75, 3.50 m^3/s) for each transport mode in "Facilities Design" (except railroad barge haul). Application costs are presented as annual costs vs. treatment plant capacity for each method discussed in "Facilities Design." However, costs of tank truck application are included in the costs of tank truck haul.

Other site-specific cost items such as land (lease or purchase), storage, field preparation (liming, grading, etc.), and monitoring are not included. The costs do not include revenues on crops harvested or credits for fertilizer not purchased.

Data Sources and Assumptions

Published reports[49–51,6,65] were the primary sources of information on costs. Because of the differing bases for cost computations, certain assumptions on sludge volumes and unit costs were utilized to arrive at generalized cost curves. Additionally, all cost figures were updated to 1978 levels with appropriate cost index (ENR 2700).

Sludge Volumes and Characteristics

The sludge was assumed to come from an activated sludge treatment plant with anaerobic digestion. Two types of sludge are considered: (1) a liquid sludge having 4 percent solids and (2) a vacuum filter cake having 20 percent solids. In either case, a base figure of 1,300 lb of dry solids per Mgal (15 g/m^3) was used.

Transportation

Transportation costs were computed using the data and procedures in reference 49. The cost curves in this reference were for the year 1975 (ENR 2200) and were based on the following values:

1. 8-hour working day
2. 2,500 gallon (9.5 m^3) diesel tank truck
3. Fuel cost of $0.60 per gallon ($158.52 per m^3)
4. Labor cost of $8.00 including fringe benefits
5. Overhead and administrative costs of 25 percent of operation and maintenance costs
6. Amortization at 7 percent for 6 years for trucks with a 15 percent salvage value
7. Amortization rate at 7 percent for 25 years for truck loading and unloading facilities, pipelines, and pumping stations.

Costs were taken from the curves and then updated to mid-1978 (ENR 2700).

Truck

For truck haul, costs were computed for a 2,500 gallon (9.5 m^3), 3-axle tanker truck with loading and unloading facilities. For a 5,500 gallon (20.8 m^3) semi unit, annual costs would be reduced by factors ranging from 1.2 for 4 Mgal/d (0.18 m^3/s) and 5 mile (8 km) one-way distance to 2.1 for an 80 Mgal/d (3.5 m^3/s) plant and 80 miles (129 km). For a 1,200 gallon (4.5 m^3), 2 axle truck, costs would increase by factors of 1.3 to 2.0 for the aforementioned wastewater flows and distances.

For dewatered sludge, costs were computed for a 15 CY (11.5 m^3), 3-axle dump truck with loading and unloading facilities and an 8-hour working day. For a 10 CY (7.6 m^3), 2 axle truck the costs would be higher by factors ranging from 1.3 for 80 Mgal/d (3.5 m^3/s), 80 mile (3.5 m^3/s) haul to 1.0 for 4 Mgal/d (0.18 m^3/s), 5 mile (8 km) haul. For a 30 CY (22.9 m^3) vehicle, costs would be reduced by factors of 0.6 to 1.0 for the aforementioned flows and distances.

For liquid sludge transport, loading and unloading facilities account for approximately 50 percent of the annual costs at 4 Mgal/d (0.18 m^3/s) flows and a 5-mile (8 km) haul distance and less than 1.5 percent for 80 Mgal/d (3.5 m^3/s) and 80 miles (129 km). For dewatered sludge, loading and unloading facilities are about 60 percent of the total annual costs at 4 Mgal/d (0.18 m^3/s) and 5 miles (8 km) and only 1 to 2 percent at 80 Mgal/d (3.5 m^3/s) and 80 miles (129 km).

Pipeline

Hydraulic computations for pipelines were based on the need to maintain a minimum velocity of 6 ft/sec (1.8 m/s). A level terrain was assumed, i.e., pumping energy was required only to overcome head losses in the pipe. A minimum diameter of 6 inches (15.2 cm) was used.

Costs include construction of the pipeline, pumping stations, and appurtenances and operating costs such as electricity (at 4¢ per kWh), labor, and materials. The costs do not cover special conditions such as hard rock excavation and highway or river crossings.

Rail and Barge

Because of their limited applicability, rail and barge transport will not be estimated in this chapter. The lack of information and the site-specific nature of these nodes would make development of generalized cost curves difficult. Further information can be found in references 49, 38, 6.

Preapplication Treatment

Preapplication treatment was assumed to be the addition of a vacuum filter to an existing activated sludge treatment plant with activated sludge thickening and anaerobic digestion of combined primary and secondary sludges. Sources of cost data include references 6 and

72a and actual plant operating records, updated to an ENR Cost Index of 2700.

Spreading

There is little information available regarding land spreading costs. This cost is highly site-specific, depending on extent of land preparation, application rate, and type of equipment (i.e., new, used, or rebuilt).

In all methods, use of new equipment was assumed. An application rate of 10 dry tons/acre·yr (22.4 Mg/ha/yr) was used to establish site acreages and costs for spraying and ridge and furrow irrigation.[51] For other methods, published costs and estimates were used.[44,48,50,52]

Summary

The cost curves are presented for treatment plant capacities of 4, 10, 40, and 80 Mgal/d (0.18, 0.44, 1.75 and 3.50 m^3/s) in figures 9–8 through 9–11, respectively. Figure 9–12 is a summary comparison of truck and pipeline unit costs for liquid sludge transport only. Costs for spreading are shown in figure 9–13. Although these costs curves are order-of-magnitude estimates only, some tentative conclusions can be drawn.

1. For small treatment plants [<10 Mgal/d (<0.44 m^3/s)] and one-way haul distances of <5 to 10 miles (8–16 km), haul of liquid sludges by truck appears to be the least expensive alternative.
2. As haul distances increase, addition of vacuum filters and hauling of dewatered sludge becomes less expensive than hauling liquid sludge. However, the savings will be partially offset by the additional cost of applying dewatered sludge.
3. As distances to the site increase, pipelines become economically competitive with trucking. The additional cost of terminal and application facilities tend to offset the savings.
4. For application of liquid sludge, no single method presents a clear economic advantage.

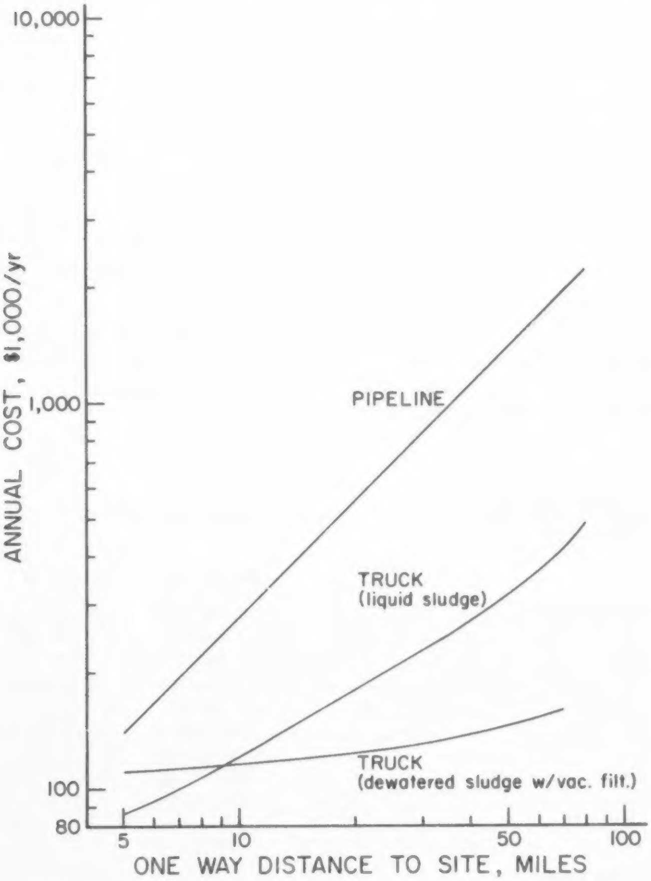

Figure 9–8.—Annual costs of sludge transport for a 4 Mgal/d treatment plant. Conditions: 15,600 gal/d liquid sludge at 4 percent solids, or 15 CY/d dewatered sludge at 20 percent solids.

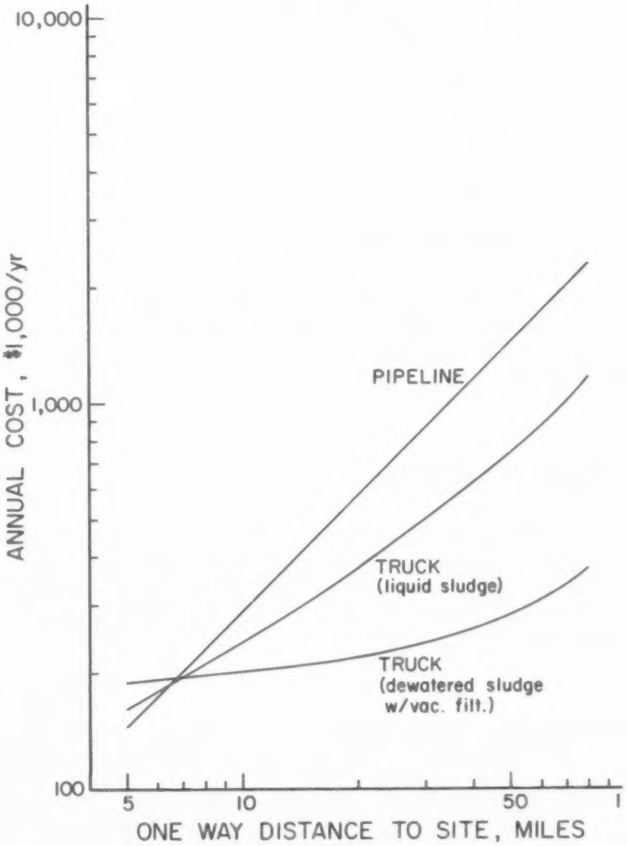

Figure 9–9.—Annual costs of sludge transport for a 10 Mgal/d treatment plant. Conditions: 38,000 gal/d liquid sludge at 4 percent solids, or 38 CY/d dewatered sludge at 20 percent solids.

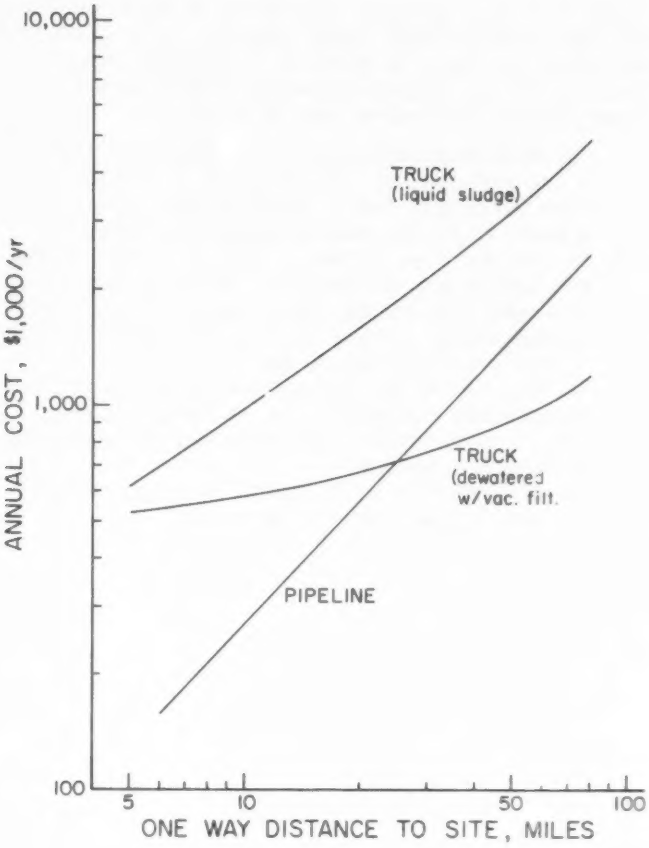

Figure 9–10.—Annual costs of sludge transport for a 40 Mgal/d treatment plant. Conditions: 156,000 gal/d liquid sludge at 4 percent solids, or 155 CY/d dewatered sludge at 20 percent solids.

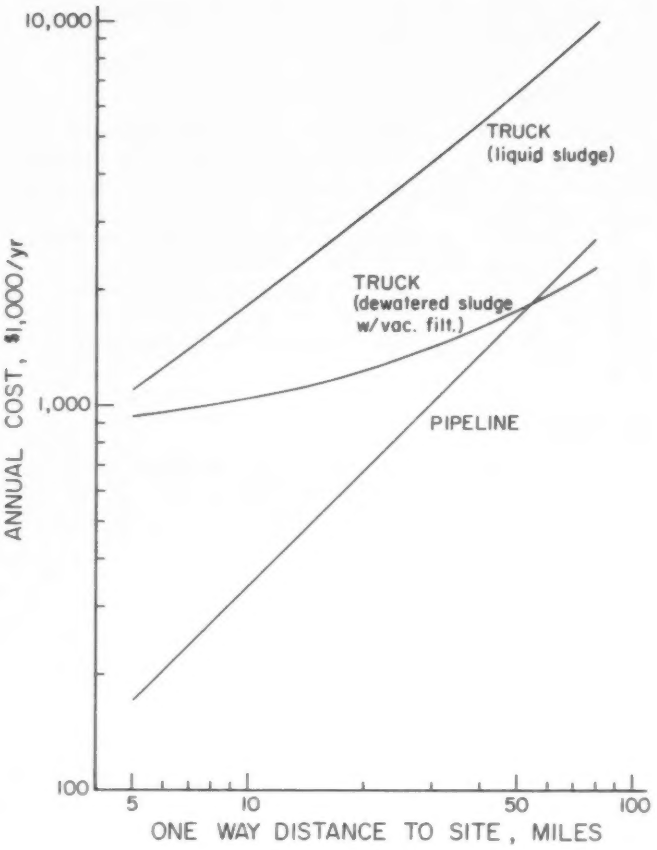

Figure 9–11.—Annual costs of sludge transport for a 80 Mgal/d treatment plant. Conditions: 312,000 gal/d liquid sludge at 4 percent solids, or 310 CY/d dewatered sludge at 20 percent solids.

DESIGN EXAMPLE A

A detailed example will be developed for a midwestern city treating 4 Mgal/d (0.18 m^3/s) of wastewater. The plant is assumed to produce 1,300 lb of sewage sludge per Mgal/d (13,490 kg/l/s), or 5,200 lb (2,360 kg) dry sludge/day.

Preliminary Planning

Sludge Composition

To illustrate the influence of sludge composition on site design, two types of sludge will be considered: one receiving predominately domestic sewage (sludge #1), and the other receiving both domestic and industrial wastes (sludge #2). The sludges have the following properties:

	Sludge #1	*Sludge #2*
Solids	4 percent	4 percent
Total N	3 percent	3 percent
NH_4-N	1 percent	1 percent
Total P	2 percent	2 percent
Total K	0.5 percent	0.5 percent
Pb	500 mg/kg	5,000 mg/kg
Zn	2,000 mg/kg	10,000 mg/kg
Cu	500 mg/kg	1,000 mg/kg
Ni	100 mg/kg	200 mg/kg
Cd	15 mg/kg	300 mg/kg

Climate

Climatological data for the application area is shown in table 9–26. Sludge application will be limited during

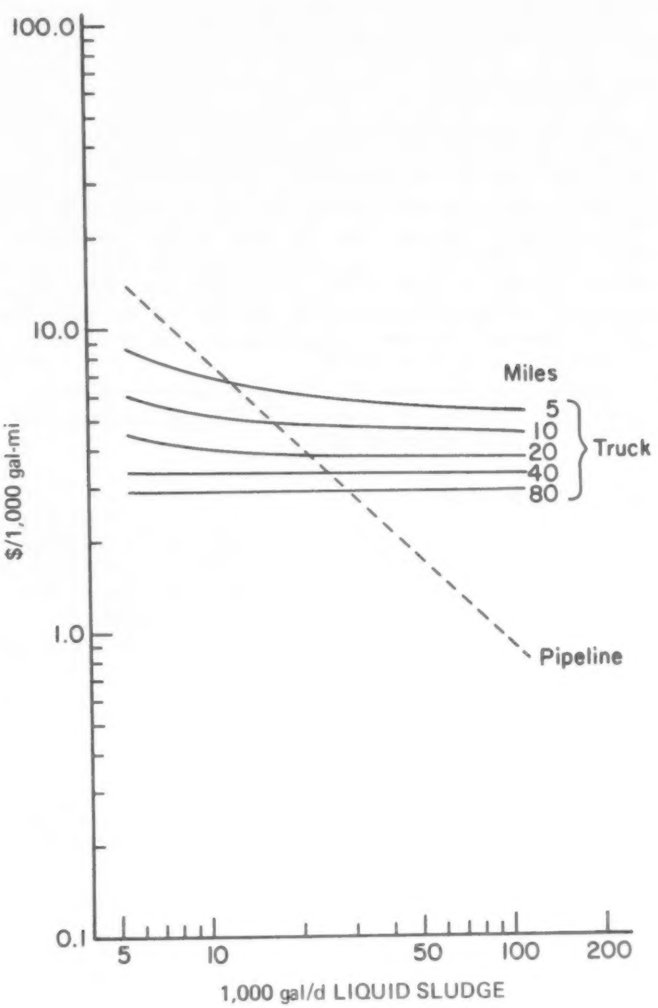

Figure 9–12.—Summary costs comparisons for transport of liquid sludge.

periods of high rainfall and high soil moisture conditions, because of the potential for surface runoff and the inability to use sludge application equipment. Sludge application will also be limited during periods of extended subfreezing temperatures due to frozen soils.

Regulations

For this site, permits are not required for sludge application provided that:

1. Annual sludge applications do not exceed the nitrogen requirement for the crop grown or 2 lbs Cd/acre (2.2 kg/ha).

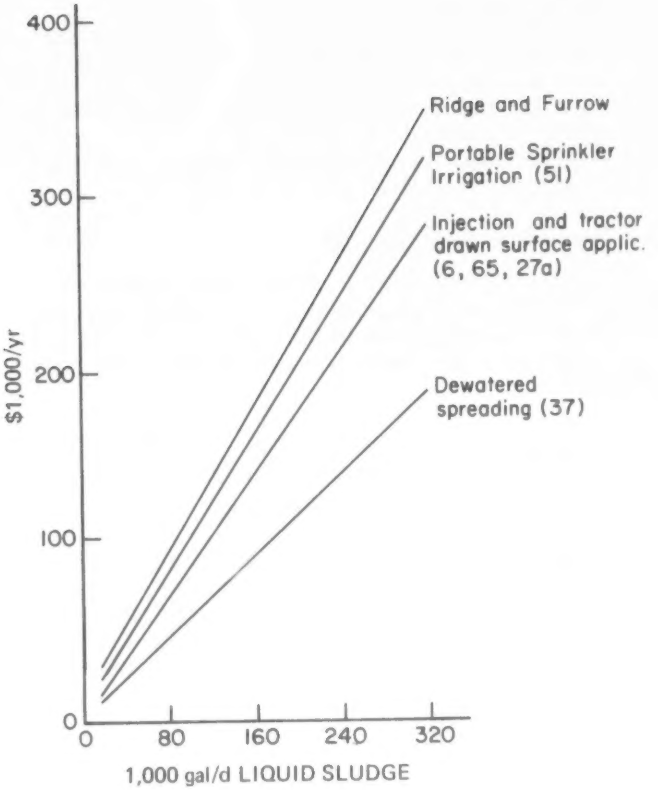

Figure 9–13.—Annual costs for application of sludge to land.

Table 9–26.—Climatological data

Month	Mean number of days	
	Precipitation ≥ 0.1 in.	≤ 32° F maximum
January	4	16
February	3	10
March	6	5
April	8	0
May	7	0
June	6	0
July	6	0
August	5	0
September	5	6
October	5	6
November	5	18
December	4	27
Total	64	88

2. Soil is maintained at pH 6.5 or above.
3. Monitoring is not needed annually other than routine soil testing to establish fertilizer recommendations and lime requirement.
4. Sewage treatment plant monitors chemical composition of sludge.
5. Records are maintained on the amount of sludge applied to each area.

Preliminary Screening

As discussed previously, a 10 ton/acre/yr (22.4 Mg/ha/yr) rate of sewage sludge is a realistic first approximation for application to agricultural soils. The acreage required for the above city can be estimated as follows:

$$\text{Acreage needed} = \frac{2.6 \text{ tons sludge/day} \times 365 \text{ days/yr}}{10 \text{ tons/acre/yr } (22.4 \text{ Mg/ha/yr})}$$

$$\cong 100 \text{ acres } (40 \text{ ha})$$

For a city with a 4 Mgal/d (0.18 m^3/s) plant, about 100 acres (40 ha) are required for sludge utilization. After contacting local extension staff, farmers, etc., the city decided to develop a detailed plan for sludge utilization on agricultural land, which is potentially available within 25 miles (40.2 km) of the treatment plant.

Site Selection

The potential sites for sludge application can be evaluated using topographic maps, soil maps, etc. For the example being considered, a soil map will be used. Figure 9–14(a) is a general soil map showing the area available for sludge utilization. A detailed soil map of the site area is shown in figure 9–14(b) and the map legend is presented in table 9–27. Since the detailed soil map is based on an aerial photo, farm buildings, houses, etc., are identifiable. The following areas can be eliminated as potential sludge application sites.

1. Towns, subdivisions, schools, and other inhabited dwellings.
2. Rivers and streams with appropriate buffer areas (e.g., 250 ft or 76.2 m).
3. Wetlands and marshes.

The remaining areas can be identified according to soil type (table 9–27). Information presented in the soil survey report includes: slope, drainage, depth to seasonal water table, depth to bedrock texture, approximate CEC, and a ranking according to suitability. The sites preferred are nearly level, well-drained, >6 ft (1.8 m) above bedrock. The ranking in table 9–27 was based on the use of soils without modification of slope or drainage. Soils with steeper slopes may be ranked higher if terraces or other erosion control practices are used to minimize runoff. Similarly, soils limited by poor drainage may be used if a tile drainage system is installed. Following ranking of the soils, the acreage available for sludge utilization can be estimated. Further evaluations must be made during on-site visits.

Site Identification

The site, as shown in figure 9–14(a) and 9–14(b), was chosen as the area best suited for land application practices. This site was chosen primarily because it was closest to the treatment plant, and had suitable soils. The maximum distance from the plant to the selected fields was estimated to be under 5 miles (8 km). Total site area covered over 2,300 acres (930 ha), but only about 100 acres (40 ha) will be needed for sludge application. Most of the area is pastureland with some cultivated fields of corn and oats.

Many alternative sites were also suitable for sludge application, but this area was selected due to its close proximity to the treatment plant.

Site Acquisition

The land area in the site was owned by 10 individuals. A contractual agreement was drawn with the individuals whereby sludges would be applied to certain fields at rates commensurate with crop nitrogen requirements. The treatment plant will transport and apply all sludge to the fields at times specified by the farmers.

Design

Soil Properties

Soils in the site area are generally silt loams, having a CEC of 10 meq/100 g. Representative soil analysis is as follows:

CEC	10 meq/100 g
Water pH	6.0
Available P	15 lb/acre
Available K	75 lb/acre
Lime (to pH 6.5)	2.4 tons/acre

Crop Requirements

Crops grown in the area include corn, soybeans, oats, wheat and pastureland. For this design example, one-half of the allocated land is cropped to orchardgrass pasture requiring 300 lb of available nitrogen/acre/yr (336 kg/ha/yr), and one-half is cropped with corn requiring 170 lb available nitrogen/acre/yr (190 kg/ha/yr). Crop fertilizer requirements were obtained from tables 9–9, 9–11 and 9–12.

Fertilizer recommendations for the two crops are as follows:

		N	*P*	*K*
	Yield	*lb/acre/yr*		
Corn	130 bu/acre	170	40	125
Orchardgrass	6 tons/acre	300	53	300

Phosphorous and potassium recommendations are based on the soil test data shown above.

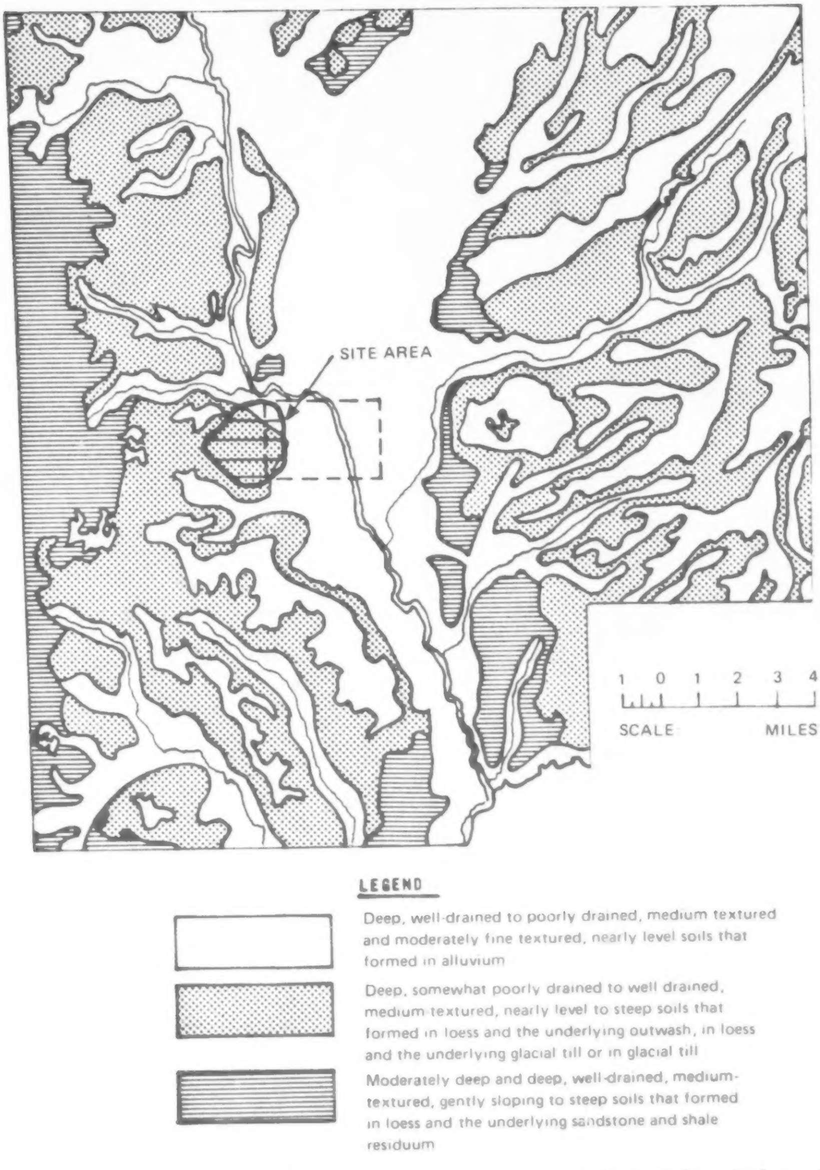
SITE AREA
1 0 1 2 3 4
SCALE MILES
LEGEND
Deep, well-drained to poorly drained, medium textured and moderately fine textured, nearly level soils that formed in alluvium
Deep, somewhat poorly drained to well drained, medium-textured, nearly level to steep soils that formed in loess and the underlying outwash, in loess and the underlying glacial till or in glacial till
Moderately deep and deep, well-drained, medium-textured, gently sloping to steep soils that formed in loess and the underlying sandstone and shale residuum

Figure 9–14(a).—General soil map showing area selected for sludge utilization.

Calculation of Annual Application Rate

Nitrogen Basis

The plant available nitrogen (N_p) in the sludge is calculated based on 100 percent availability of NH_4-N and 20 percent availability of organic N during the year of sludge application. The sludge does not contain detectable amounts of NO_3-N, so only NH_4-N and total N are needed to calculate plant available nitrogen (N_p). The calculation of N_p is as follows:

Lbs N_p/ton sludge

$$= \text{percent } NH_4\text{-N} \times 20 + \text{percent organic-N} \times 4$$

$$= 1 \times 20 + 2 \times 4$$

$$= 28$$

This value of N_p applies to both sludge #1 and #2,

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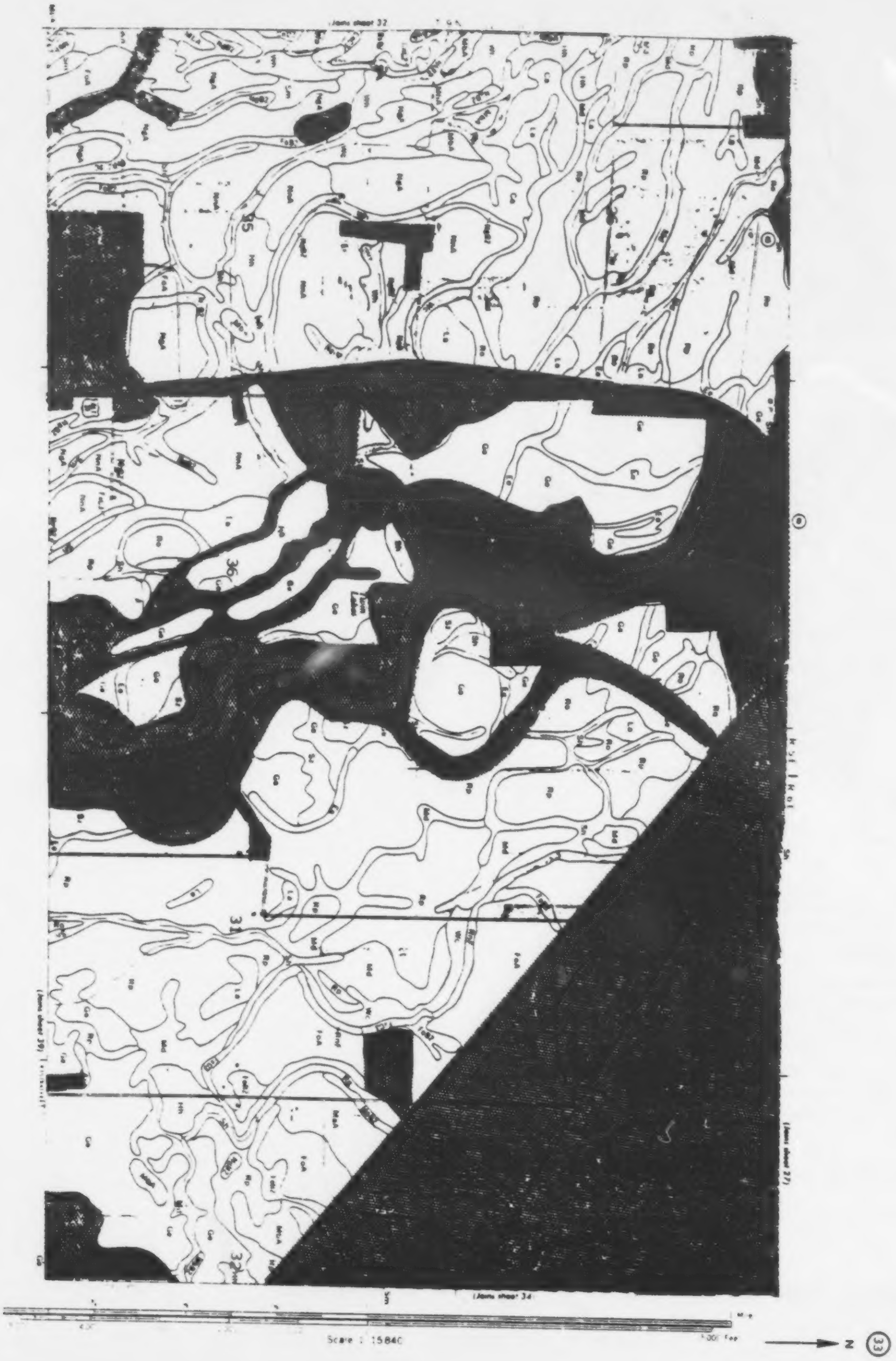
(Joins sheet 32)
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35
36
Scale 1:15840
1 Mile
5000 Feet
N
33

Figure 9–14(b).—Detailed soil survey map of potential site for sludge application (areas not suited for use are shaded).

Table 9–27.—Ranking of soil types for sludge application

Soil type	Slope percent	Depth to: Seasonal high water table (ft)	Depth to: Bedrock (ft)	Texture[a]	Drainage class[b]	Approximate CEC	Relative ranking[c]
AvA.........	0–2	1–3	>15	sil	P	10–15	3
Ca..........	0.2	>6	>15	sil	W	10–15	1
CnB2.......	2–6	>6	>15	sil	W	10–15	1
CnC2.......	6–12	>6	>15	sil	W	10–15	2
CnC3.......	6–12	>6	>15	sil	W	10–15	2
CnD2.......	12–18	>6	>15	sil	W	10–15	3
CnD3.......	12–18	>6	>15	sil	W	10–15	3
Ee..........	0–2	3–6	>15	sil	W	10–15	2
FoA.........	0–2	>6	>15	l	W	10–15	1
FoB2.......	2–4	>6	>15	l	W	10–15	1
FxC3.......	6–12	>6	>15	l	W	10–15	2
Ge..........	0–2	>6	>15	l	W	10–15	1
Hh..........	0–2	1–3	>10	sil	SP	10–15	3
La..........	0–2	>6	>15	gsal	W	<5	1
MbA........	0–2	>6	>15	l	W	10–15	1
MbB2.......	2–6	>6	>15	l	W	10–15	1
Md..........	0–2	3–6	>15	sicl	MW	>15	2
NgA........	0–2	>6	>15	l	W	10–15	1
NgB2.......	2–6	>6	>15	l	W	10–15	1
NnA........	0–2	>6	>15	l	W	10–15	1
RnF.........	0–2	>6	>15	gl	E	<5	1
Ro..........	0–2	>6	>15	sicl	W	>15	1
Rp..........	0–2	>6	>15	sicl	W	>15	1
RsB2.......	2–6	3–6	>15	sil	MW	10–15	2
Sc..........	0–2	0–1	>15	sicl	VP	>15	3
Sh..........	0–2	1–3	>15	sil	SP	10–15	3
Sm..........	0–2	1–3	>15	l	SP	10–15	3
Sz..........	0–2	>6	>15	sal	W	5–10	1
Wc..........	0–2	0–1	>15	cl	VP	>15	3
Wh..........	0–2	1–3	>15	l	SP	10–15	3

[a] l, loam; gsal, gravelly sandy loam; sil, silt loam; sicl, silty clay loam; cl, clay loam; sal, sandy loam; gl, gravelly loam.

[b] E, exclusively drained; W, well drained; MW, moderately well drained; SP, somewhat poorly drained; P, poorly drained; VP, very poorly drained.

[c] 1, 0–6 percent slope, >6 ft to water table and >15 to bedrock. 2, 6–12 percent slope or 3–6 ft to water table. 3, 12–18 percent slope or 0–3 ft to water table.

since their total and NH_4 nitrogen contents are the same. After obtaining N_p, the annual sludge application rate (tons/acre) is calculated by dividing N_p into N required by the crop. For corn,

$$\text{tons/sludge/acre} = \frac{170}{28}$$

$$= 6.1$$

For orchardgrass, surface applications are used whereby approximately 50 percent of the NH_4-N applied will be lost by NH_3 volatilization. The available N content is then decreased and N_p is calculated from

Lbs N_p/ton sludge

$$= \text{percent } NH_4\text{-N} \times 10 + \text{percent organic N} \times 4$$

$$= 1 \times 10 + 2 \times 4$$

$$= 18$$

(NOTE: The conversion factor for NH_4-N has been decreased by 50 percent)

For orchardgrass, the annual application rate is:

$$\text{tons sludge/acre} = \frac{300}{18}$$
$$= 16.7$$

The above calculations apply to the first application of sludge; however, the contribution of residual N to the plant available N pool becomes important in the years following initial sludge application. Based on the data in table 9–13, additions of sludge containing 2 percent organic N will release 1.0, 0.9, and 0.9 lbs N/ton (0.5, 0.45, and 0.45 kg/Mg) sludge applied for the first, second, and third years following sludge application. These residual N values are subtracted from the crop N requirements. The rate calculations for the corn and orchardgrass crops considered are summarized below:

Corn (incorporated sludge)

Year	*Calculation*	*Tons/acre*
1........	$\frac{170 - 0}{28}$	6.1
2........	$\frac{170 - (6.1 \times 1.0)}{28}$	5.8
3........	$\frac{170 - (6.1 \times 0.9) - (5.8 \times 1.0)}{28}$	5.7
4........	$\frac{170 - (6.1 \times 0.9) - (5.8 \times 0.9) - (5.7 \times 1.0)}{28}$	5.5
5........	$\frac{170 - (5.8 \times 0.9) - (5.7 \times 0.9) - (5.5 \times 1.0)}{28}$	5.5

Orchardgrass (surface application)

Year	*Calculation*	*Tons/acre*
1........	$\frac{300 - 0}{18}$	16.7
2........	$\frac{300 - (16.7 \times 1.0)}{18}$	15.7
3........	$\frac{300 - (16.7 \times 0.9) - (15.7 \times 1.0)}{18}$	15.0
4........	$\frac{300 - (16.7 \times 0.9) - (15.7 \times 0.9) - (15 \times 1.0)}{18}$	14.1
5........	$\frac{300 - (15.7 \times 0.9) - (15.0 \times 0.9)(14.1 \times 1.0)}{18}$	14.4

Cadmium Basis

In addition to considering the annual rate of N addition, the rate of Cd must be kept below 2 lb/acre/yr (2.24 kg/ha/yr). Currently it is felt that limiting Cd to 2 lb/acre/yr (2.24 kg/ha/yr) will minimize the accumulation of Cd in most crops, providing soil pH is maintained at 6.5 or above. The 2 lb/acre/yr (2.24 kg/ha/yr) limit should be considered tentative because ongoing and future research may provide data for a more valid Cd criteria. The rate of sludge application to limit Cd to 2 lb/acre/yr (2.24 kg/ha/yr) is calculated:

Sludge #1

$$\text{Tons/acre/yr} = \frac{2 \text{ lb Cd/acre/yr}}{15 \times 0.002} = 66.7$$

Sludge #2

$$\text{Tons/acre/yr} = \frac{2 \text{ lb Cd/acre/yr}}{300 \times 0.002} = 3.3$$

A comparison of the rates based on N and Cd for sludges #1 and #2 indicate that N application rates can be used for sludge #1 but not for sludge #2. Only 3.3 tons/acre/yr (7.40 Mg/ha/yr) of sludge #2 can be applied, requiring supplemental fertilizer additions for optimum crop yield.

Total Amount of Sludge Applied

The total amount of sludge that can be applied for the life of a site is based on the metal loadings as calculated from the metal content of the sludge and the data shown in table 9–14. The total sludge loadings are calculated as follows for sludge #1.

Metal	*Total metal limit (lbs/acre)*	*Metal content of sludge (ppm)*	*Calculation*	*Total amount of sludge allowed (tons/acre)*
Pb......	1,000	500	$\frac{1{,}000}{500 \times .002}$	1,000
Zn......	500	2,000	$\frac{500}{2{,}000 \times .002}$	125
Cu......	250	500	$\frac{250}{500 \times .002}$	250
Ni......	100	100	$\frac{100}{100 \times .002}$	500
Cd......	10	15	$\frac{10}{15 \times .002}$	325

The above calculation indicates that Zn will control total sludge applications for sludge #1 at 125 tons/acre (280.3 Mg/ha) . Obviously, if pretreatment procedures could be instituted to reduce Zn inputs to the treatment system, the site life could be increased substantially. Using 5.5 and 14.5 tons/acre (12.3 and 32.5 Mg/ha) for corn and orchardgrass, respectively, the site life can be calculated as follows:

Crop	*Calculation*	*Site life*
Corn..	$\frac{125 \text{ tons/acre}}{5.5 \text{ tons/acre/yr}}$	22.7
Orchardgrass..............................	$\frac{125 \text{ tons/acre}}{14.5 \text{ tons/acre/yr}}$	8.6 yrs

The total amount of sludge #2 that can be applied is calculated similarly.

Metal	*Total metal limit (lbs/acre)*	*Metal content of sludge (ppm)*	*Calculation*	*Total amount of sludge allowed (tons/acre)*
Pb.....	1,000	5,000	$\frac{1{,}000}{5{,}000 \times .002}$	100
Zn.....	500	10,000	$\frac{500}{10{,}000 \times .002}$	25
Cu.....	250	1,000	$\frac{250}{1{,}000 \times .002}$	125
Ni......	100	200	$\frac{100}{200 \times .002}$	250
Cd.....	10	300	$\frac{10}{300 \times .002}$	17

Based on the above calculation, total sludge additions would be limited to 17 tons/acre (38.1 Mg/ha) for sludge #2 due to the Cd concentration in the sludge. At 3.3 tons/acre/yr (7.4 Mg/ha/yr), the site life would be approximated to 5.2 years.

Phosphorous and Potassium Requirements

Fertilizer recommendations for these two elements will vary according to the amount of sludge added to the soil. Sludge application rates are presented in tables 9–28 and 9–29, that include P and K additions and requirements.

Land Area Required

Application rates for one-half of the land area cultivated in corn will require 5.5 tons/acre/yr (12.3 Mg/ha/yr), whereas areas of orchardgrass will require 14.5 tons/acre/yr (32.5 Mg/ha/yr). Calculation of land area required for sludge #1, after a four year period is as follows:

$$\text{Acres} = \frac{949 \text{ tons/yr}}{(5.5 + 14.5)/2\text{tons/acre/yr}}$$
$$= 94.9$$

The total amount of land required for sludge #2 is calculated at 3.3 tons/acre/yr (7.4 Mg/ha/yr) (based on Cd limits).

$$\text{Acres} = \frac{949 \text{ tons/yr}}{3.3 \text{ tons/acre/yr}}$$
$$= 288$$

Table 9–28.—Application schedule for sludge #1

Year	Sludge applied (tons/acre)		N applied[b] (lbs/acre)	N residual (lbs/acre)	P applied (lbs/acre)	P needed[c] (lbs/acre)	K applied (lbs/acre)	K needed[d] (lbs/acre)
	Annual	Cumulative[a]						
Corn								
1............................	6.1	6.1	170	0	243	0	61	64
2............................	5.9	11.9	164	6	234	0	59	66
3............................	5.7	17.6	159	11	227	0	57	68
4............................	5.5	23.1	154	16	219	0	55	70
to								
22...........................	5.5	122.4	155	15	221	0	55	70
Orchardgrass								
1............................	16.7	16.7	360	0	667	0	167	133
2............................	15.8	32.4	284	16	631	0	158	142
3............................	15.0	47.4	269	31	599	0	150	150
4............................	14.2	61.6	256	44	569	0	142	158
5............................	14.3	76.0	258	42	574	0	143	157
6............................	14.4	90.4	260	40	577	0	144	156
7............................	14.4	104.8	260	40	577	0	144	156
8............................	14.4	119.3	260	40	577	0	144	156

[a] Total cumulative not to exceed 125 tons/acre (Zn unit).

[b] Amount of available N applied to meet crop N requirement.

[c] No fertilizer P needed.

[d] Fertilizer K needed to meet crop K requirement.

Table 9–29.—Application schedule for sludge #2

Year	Sludge applied (tons/acre)		N applied (lbs/acre)	N residual (lbs/acre)	N needed (lbs/acre)	P applied (lbs/acre)	P needed[b] (lbs/acre)	K applied (lbs/acre)	K needed[c] (lbs/acre)
	Annual	Cumulative[a]							
Corn									
1	3.3	3.3	92	0	78	132	0	33	92
2	3.3	6.6	92	3	75	132	0	33	92
3	3.3	9.9	92	6	72	132	0	33	92
4	3.3	13.2	92	9	69	132	0	33	92
5	3.3	16.5	92	9	69	132	0	33	92
Orchardgrass									
1	3.3	3.3	92	0	208	132	0	33	257
2	3.3	6.6	92	3	205	132	0	33	257
3	3.3	9.9	92	6	202	132	0	33	257
4	3.3	13.2	92	9	199	132	0	33	257
5	3.3	16.5	92	9	199	132	0	33	257

[a] Sludge #2 application is limited by Cd at 3.3 tons/acre/yr for 5 yrs.

[b] No P fertilizer needed as P added in sludge exceeds crop requirement.

[c] Fertilizer K needed to supply 125 and 300 lbs K/acre for corn and orchardgrass, respectively.

Stabilization

A variety of stabilization techniques are available. For the purpose of this example, it is assumed that sludge undergoes anaerobic digestion. Characteristics for this process, and other stabilization processes are presented in table 9–18.

Dewatering

An additional consideration in the design of a system is the relative advantages associated with dewatering sludges. For example, a comparison can be made of liquid versus dewatered sludge for transportation and application costs, annual application rates and site life.

Dewatered sludge contains less NH_4-N than liquid sludge resulting in increased annual application rates. If the rate is controlled by Cd, dewatering will decrease the amount of plant available N added per year, necessitating additional N fertilizer to optimize crop yields. Annual application rates and site life for sludge #1 following dewatering are shown in table 9–30. Since the site life depends on metal additions, the use of low NH_4-N sludges results in a reduced site life. However, the larger annual rates result in less land needed per year.

Table 9–30.—Effect of NH_4-N concentration in sludge on annual application rates for addition of 200 lbs N/acre

Percent NH_4-N in sludge[a]	Years of sludge application (tons/acre)					Site life[b] (years)
	1	2	3	4	5	
0	25.0	22.0	19.5	17.3	18.2	6
0.25	15.4	14.2	13.2	12.3	12.5	10
0.5	11.1	10.5	10.0	9.5	9.6	13
0.75	8.7	8.3	8.0	7.7	7.7	16
0.90	7.7	7.4	7.1	6.9	6.9	18

[a] Sludge contains 2 percent organic N. Liquid sludge at 4 percent solids contained 1 percent NH_4-N. The NH_4-N levels at 8 percent and 16 percent solids would be 0.5 and 0.25 percent NH_4-N, respectively.

[b] Assumes total sludge addition is limited to 125 tons/acre, as for sludge #1.

Transportation and Application

After deciding upon an area for sludge application, the various alternatives for transportation and application methods can be considered. Costs for transportation can be estimated from the curves presented in "Costs." At a distance of 5 miles (8 km), figure 9–8 shows that truck transport of liquid sludge is the least expensive alternative.

Using the criteria specified in "Costs," costs for a 5 mile (8 km) one-way truck haul from figure 9–8 would be \$86,000/yr. The cost would be \$91/dry ton (\$100/Mg), or about \$3.70/wet (\$4.08/Mg) ton of sludge. For a pipeline, the annual cost would be \$140,000 plus cost of application at the site.

Many assumptions were used in calculating the curves presented in "Costs." Many of these assumptions are not applicable for any specific site (i.e., labor costs, type and size of truck, loading facilities, etc.).

Costs for spreading sludge #2 would increase primarily because more land is required, increasing application costs. Dewatering would be advantageous only in reducing volume, since the same rates of solids must be applied.

Storage

In the midwestern climate used for this example, storage facilities will be needed during the winter months because of frozen soils and wet soil conditions. If soil freezing is not severe, sludge application could continue if injection equipment is used during the winter. Based on the data in table 9–26, the estimated number of days when sludge could not be applied is approximately 100. Assuming a 100 day storage requirement, the amount of storage can be calculated:

$$\text{tons storage} = 100 \text{ days} \times 2.6 \text{ tons sludge/day}$$
$$= 260 \text{ tons sludge}$$

If the sludge is 5 percent solids, then storage would be needed for 5,200 wet tons (4717 Mg) of approximately 1.2×10^6 gallons (4,500 m^3). A lagoon or other storage facility of 100 ft × 100 ft × 20 ft (30 m × 30 m × 6 m), or 200,000 cu ft (5,660 m^3), would suffice.

Application Schedule

For a typical year, an application schedule can be formulated for the crops considered.

Month	*Corn*	*Orchardgrass*
January	NA	NA
February	NA	NA
March	SI	S
April	SI	S
May	C	S
June	C	S
July	C	S
August	C	S
September	C	S
October	SI	S
November	SI	S
December	NA	NA

NA, no application (e.g., frozen ground); S, surface application; SI, surface or injection application; C, growing crop present.

The above table indicates the probable months of the year that sludge can be applied on the crops. More than 3 months of storage would be needed if inclement climatic conditions were encountered during periods of sludge application.

Split applications of sludge may be required for rates of liquid sludge in excess of 5 dry tons/acre (11.2 Mg/ha). Split applications refer to adding small quantities of sludge at different times of the year to attain the desired total rate. If the sludge contains 4 percent solids, the volume of sludge applied at a 5 ton/acre (11.2 Mg/ha) rate is $\sim$23,500 gallons (90 m^3) or $\sim$0.9 acre-in Realizing that surface runoff depends on soil properties (e.g., infiltration rate) and slope, the likelihood of runoff from relatively flat soils (less than 5 percent slope) is increased when application rates approach 1 acre-in. of liquid sludge. Obviously, subsurface application will minimize runoff from all soils. An advantage of split application is the increased efficiency of N utilization by the crops grown.

Monitoring

The recommendations developed are based on minimizing NO$_3$-N movement into groundwater and Cd uptake by plants. Therefore, the monitoring program would consist of continuing soil analysis every 2 to 3 years for plant available P and K and lime requirement. To preclude excessive plant availability of metals, mainly Cd, the soil must be maintained at pH $\geq$6.5.

Additional Cropping Patterns

To simplify the design example, only two crops were considered. However, in many situations sludge will be applied to more than two crops. It is suggested that application rate calculations be made for all crops grown when the detailed plan is developed. For Design Example A, additional crops could be wheat, oats, barley and soybeans. The results of these calculations are shown in tables 9–31 and 9–32.

DESIGN EXAMPLE B

Preliminary Planning

This example will illustrate the procedure used for a 40 Mgal/d (1.75 m^3/s) treatment plant. The total amount of sludge requiring utilization is 9,490 tons/year (8610 Mg/yr). The preliminary analysis based on a 10 ton/acre (22.4 Mg/ha) application indicates that approximately 1,000 acres (405 ha) would be needed (or 10 times the area for a 14 Mgal/d (0.6 m^3/s) plant). Assuming that initial inquiries suggest that land is available, the procedures outlined for Design Example A would be followed. An additional consideration for a 40 Mgal/d (1.75 m^3/s) plant would be the possibility of the city purchasing land to increase their operational flexibility. The major advantage in purchasing land is that the rate of sludge applied can add in excess of 2 lb Cd/acre/year (2.2 kg/ha/yr) and in excess of the N required by the crop, provided adequate monitoring procedures are used. The major monitoring requirements are (1) all crops are analyzed for metals, mainly Cd, prior to consumption by livestock or marketed and (2) ground and surface waters are monitored to prevent off-site degradation of water

Table 9–31.—Application rates for sludge #1 on soils cropped to oats or winter wheat

Year	N required (lbs/acre)	Residual N (lbs/acre)	P added[a] (lbs/acre)	K added (lbs/acre)	K fertilizer (lbs/acre)	Annual rate (tons/acre)	Cumulative amount (tons/acre)
			Incorporated (0 percent NH_3 lost)				
1.............	100	0	143	36	39	4	4
2.............	97	3	138	34	41	3	7
3.............	93	7	133	33	42	3	10
4.............	90	10	129	32	43	3	13
5.............	91	9	130	32	43	3	16
6.............	91	9	130	32	43	3	19
7 to 39.....	91	9	130	32	43	3	127
			Surface applied (50 percent NH_3 lost)				
1.............	100	0	222	56	19	6	6
2.............	95	5	210	53	22	5	11
3.............	90	10	200	50	25	5	16
4.............	85	15	190	47	28	5	21
5.............	86	14	192	48	27	5	26
6.............	87	13	193	48	27	5	31
7 to.........	87	13	193	48	27	5	126

[a] No fertilizer P needed.

Table 9–32.—Application rates for sludge #1 on soils cropped to soybeans

Year	N required (lbs/acre)	Residual N (lbs/acre)	P added[a] (lbs/acre)	K added (lbs/acre)	K fertilizer (lbs/acre)	Annual rate (tons/acre)	Cumulative amount (tons/acre)
			Incorporated (0 percent NH_3 lost)				
1.............	250	0	357	89	11	9	9
2.............	241	9	345	86	14	9	18
3.............	233	17	333	83	17	8	26
4.............	226	24	323	81	19	8	34
5.............	227	23	324	81	19	8	42
6.............	227	23	325	81	19	8	50
7 to 15.....	227	23	325	81	19	8	122
			Surface applied (50 percent NH_3 lost)				
1.............	250	0	556	139	0	14	14
2.............	237	13	526	131	0	13	27
3.............	224	26	499	125	0	12	39
4.............	213	37	474	118	0	12	51
5.............	215	35	478	120	0	12	63
6.............	216	34	481	120	0	12	75
7 to 10.....	216	34	481	120	0	12	123

[a] No fertilizer P needed.

quality from movement of pathogens, N, P, metals, etc. Thus, neither annual Cd nor total metal limits are applicable to soils dedicated to sludge disposal.

To minimize problems from NO_3 leaching into groundwater, the annual rate of sludge application is related to N use by the crop grown. The annual N application can be increased above the fertilizer recommendation for dedicated sites subject to monitoring. For this example, the amount of N applied will be 1.5 times the fertilizer recommendation.

Design

Application Rates

The crops chosen are corn and orchardgrass as in Design Example A. The application rate average, fertilizer needs, etc., would be the same as those presented earlier in Design Example A.

Corn was selected because it excludes Cd from the grain to a greater extent than other crops (e.g., soybeans). Corn and orchardgrass also have the ability to remove relatively large amounts of N during the growing season.

Surface application of sludge will be used to minimize the land required. Only N is considered in calculating the surface application rate. For sludge #1 and #2:

Crop	*N needed*	*N added*	*Application rate, tons/acre*	*Acres needed*
Corn	170	255	14.2	668
Orchardgrass	250	375	20.8	456

Note: N added = 1.5 × N needed.

Approximately 460 acres (186 ha) would be required for utilization of all sludge from a 40 Mgal/d (1.75 m^3/s) plant (9,490 tons/year or 8,609 Mg) if orchardgrass, or a similar cover crop were used, whereas 670 acres (271 ha) would be needed if corn were grown. Both the forage and corn crop could be harvested and marketed as long as metal analyses indicate that the crops do not contain excessive concentrations of Cd or other methods. Guidance from FDA will be needed to assess acceptable levels of metals in grains and forages.

The quantity of land purchased by the city would depend on the acreage of private farmland available presently and in the future. The city purchased 550 acres (223 ha) similar to figure 9–14a and 9–14b and utilized it as follows:

Crop	*Application rate, tons/acre*	*Acres*	*Sludge applied, tons*
Corn	14.2	350	4,790
Orchardgrass	20.8	200	4,160
			9,130

Using this distribution approximately 360 tons (326 Mg) would be applied to privately owned cropland. If the availability of private cropland decreases, the corn acreage can be decreased and the forage acreage increased to utilize all city-owned land most economically. If all 550 acres (223 ha) were cropped to orchardgrass, 11,440 tons (10,380 Mg) could be utilized each year or 120 percent of the sludge produced.

Application Methods

Potential application methods for each crop include:

Crop	*Application method*
Corn	Surface—prior to planting and post harvest Ridge and furrow irrigation—during growing season
Orchardgrass	Surface—post-harvest

As discussed in Design Example A, split applications will be needed for a sludge with 4 percent solids to attain the desired application rates. The volume of liquid sludge applied will be 3.0 and 4.4 acre-in./year for the corn and orchardgrass areas, respectively.

The months available for application are given below:

Month	*Corn*	*Orchardgrass*
January	NA	NA
February	NA	NA
March	S	S
April	S	S
May	S	S
June	R & F	S^{-H}
July	R & F	S^{-H}
August	R & F	S
September	R & F	S^{-H}
October	H	S^{-H}
November	S	S
December	NA	NA

NA, No application; S, surface; R & F, ridge and furrow irrigation; H, harvest crop.

The orchardgrass can be harvested 3–4 times per year while corn is harvested in October or November. Management is needed to insure that sludge applications are timed appropriately to allow relatively dry soil conditions during harvest operations. For sludges containing persistent organics (i.e., PCB's) at concentrations >10 mg/kg, surface application to forages is not recommended.

Site Use

The site life for a dedicated system is difficult to predict based on present knowledge. However, the criteria for privately owned farmland are conservative to allow growth of any crop after sludge application ceases. It is likely that the total amount of metals applied to dedicated sites can be greater than those shown in table 9–14. The most essential factor in minimizing movement and plant uptake of metals is maintaining soil pH at 6.5 or above.

Transportation and Application

The sludge transportation system adopted will depend on local conditions such as availability of rail lines, etc.

The data in figure 9–10 indicate that a pipeline is economically feasible for a 40 Mgal/d (1.75 m^3/s) plant with transportation distances of less than 25 miles (40 km). The estimated costs/year for a site 10 miles (16 km) from the plant are:

	Pipeline	*Truck*
Transportation	$27,000	$980,000
Surface application (80 percent of volume)	110,000	(included)
Ridge and furrow (20 percent of volume)	50,000	(included)
Total	187,000	980,000

Unit costs are $19.70/dry ton ($21.71/Mg) or $0.80/wet ton ($0.88/Mg) for sludge applied to the dedicated site via a pipeline and ridge and furrow irrigation plus surface application. For truck transport and surface application, costs are $103.30 and $4.13 per dry and wet ton ($113.86 and $4.55/Mg), respectively.

Monitoring

Strict monitoring procedures are needed on dedicated sludge disposal sites. The monitoring procedures discussed in the Process Design Manual for Land Treatment of Municipal Wastewater[31] are also applicable to sludge sites.

1. Groundwater—locate wells to sample on-site, perimeter and background. Proper location and depth of wells is essential to obtain reliable data on changes in groundwater quality.
   a. Quarterly analyses—Total N, NO_3^-, total P, soluble P, Pb, Zn, Cu, Ni, Cd, coliforms.
   b. Optional analyses—BOD, COD, pH, total dissolved solids, alkalinity, SAR.
2. Soils—annual analyses of soil samples are recommended to monitor accumulation of metals and changes in soil pH. Soils are sampled at 0–6 inches, 6–12 inches and 12–24 inches, or within homogeneous horizons.
   a. Required analyses—pH, lime requirement, plant available P and K, and extractable or total Pb, Zn, Cu, Ni and Cd.
   b. Optional analyses—CEC, organic C, total N, total P, base saturation, organics.
3. Plants—metal analyses are required on all grain or forages utilized by livestock or marketed. The metals of main concern are Pb, Ni and Cd. Optional analyses would include total N, P, K, Cu and Zn. Nitrate analysis is suggested for crops consumed by livestock.

DESIGN EXAMPLE C

This example will illustrate the application of sludges on forest land. The sludge composition, climate and soil characteristics are the same as in Design Example A.

The data required are

Sludge:	
Solids	4 percent
Organic N	2 percent (dry weight basis)
NH_4^+-N	1 percent (dry weight basis)
Climate:	
Rainfall	40 in (101.6 cm).
Deciduous trees:	
Annual N uptake	50 lbs/acreage (56.0 kg/ha) (table 9–16)
Evapotranspiration	17 in./yr (43.2 cm/yr) (table 5–36 in ref. 31)
Percolate NO_3^--N	10 mg/l

The available N content of the sludge is calculated as in Design Example A:

$$\begin{aligned}\text{Percent } C_s &= \text{percent organic N} \times 0.2 + \text{percent } NH_4^+\text{-N} \\ &= 2 \text{ percent} \times 0.2 + 1 \text{ percent} \\ &= 1.4\end{aligned}$$

The available N content is next converted to a volume basis and related to N applied,

$$L_n = 22.7\ C_s L_s S$$

where

L_n = plant available N applied (lbs/acre · yr)
L_s = volume of sludge applied (in./yr)
S = percent solids in liquid sludge

(Conversion factors assume 1 ft^3 of sludge = 62.4 lbs or 1 in/acre = 2.26×10^5 lbs.)

For a sludge containing 4 percent solids,

$$\begin{aligned}L_n &= 22.7(1.4)L_s(4) \\ &= 127.1\ L_s\end{aligned}$$

or

$$L_s = 0.0079\ L_n$$

The climatic data and ET are used to calculate the volume of percolate

$$L_s + Pr = W_p - ET$$

where

Pr = precipitation (in./yr)
W_p = percolate volume (in./yr)
ET = evapotranspiration (in./yr)

For the data used,

$$L_s + 40 = W_p + 17$$

or

$$W_p = L_s + 40 - 17$$

$$W_p = L_s + 23$$

Substituting L_s from above,

$$W_p = 0.0079\ L_n + 23$$

This information is then used in the following equation to calculate plant available N that can be applied.

$$L_n = U + D + 0.23\ W_p C_p$$

where

U = N uptake by plants (lbs/yr)
D = denitrification factor ($0.2\ L_n$)
C_p = percolate NO_3-N concentration (10 mg/l)

Substituting the previous values into the above equation yields

$$L_n = 50 + 0.2\ L_n + 0.23(0.0079\ L_n + 23)10$$

$$L_n = 50 + 0.2\ L_n + 0.018\ L_n + 52.9$$

Solving for L_n,

$$L_n - 0.2\ L_n - 0.018\ L_n = 102.9$$

$$0.78\ L_n = 102.9$$

$$L_n = 132$$

Thus, 132 lb (59.9 kg) of plant available N could be applied to the deciduous tree stand considered. It should be emphasized that these calculations assume that 50 lb (22.7 kg) of N are utilized by the trees and that 20 percent of available N applied is lost through denitrification.

The volume of liquid sludge applied can be calculated from,

$$L_n = 22.7\ C_s L_s S$$

$$132 = 22.7(1.4)L_s(4)$$

$$L_s = \frac{132}{22.7(1.4)(4)}$$

$$= 1.04 \text{ in.}$$

This rate is equivalent to 118 wet tons/acre (264 Mg/ha) of 4.7 tons/acre (10.5 Mg/ha).

This example shows the relatively small influence of water applied with the sludge on the total volume of percolate. For dewatered and liquid sludges containing >5 percent solids, the volume of sludge applied can be ignored in the calculation of W_p.

The contribution of residual N to L_n can be used if sludge has been applied previously to the site. For a sludge with 2 percent organic N, approximately 1 lb N/ton will be released the second year and 0.9 lb N/ton in the third and fourth years after application. Thus, the rates of sludge applied would be:

Year	*N applied*	*Residual N*	*Sludge applied, tons/acre*
1	132	0	4.7
2	127	4.7	4.6
3	123	8.8	4.4
4	119	12.8	4.3

As shown for Design Example A, the amounts P, K, and metals can be calculated once the sludge application rate is known.

It should be re-emphasized that the use of the above design criteria is based on wastewater irrigation considerations but it, hopefully, will simulate the responses occurring when forest lands are treated with sludge. A more conservative estimate can be made by assuming that no N uptake by plants occurs, relying upon denitrification to reduce the NO_3-N concentration to 10 mg/l in the percolate. For this case, the rate of sludge application would be approximately 2.4 tons/acre (5.4 Mg/ha).

Appendix A: ENVIRONMENTAL IMPACTS

Soils

General Properties

Soil is a complex mixture of inorganic and organic compounds. The inorganic fraction may consist of clay minerals, other silicate minerals, oxides, and carbonates. The organic fraction usually contains humic and nonhumic substances. The proportions and properties of inorganic and organic components in soils are a function of time, climate, topography, vegetation and parent material. In a well-aggregated soil, soil particles and pore space each constitute 50 percent of the volume. Optimum conditions for plant growth exist when water and air each occupy 50 percent of the pore space. With respect to the solid phase, the texture of a soil is defined by the relative proportion of particles found in the sand ($>50\mu$), silt (2–50μ) and clay ($<2\mu$) size fractions. Through use of a texture triangle, a soil containing a certain percentage of sand, silt and clay is assigned a name, such as sandy loam, silt loam, silty clay loam, etc. In this context, the term clay is used to define a size fraction, which may contain inorganic compounds in addition to clay minerals.

Clay minerals, one of the more important inorganic fractions of a soil, are composed of layered sheets of tetrahedrally, or octahedrally coordinated cations. The sheets of Si tetrahedra and Al octahedra are present in a 1:1 or 2:1 configuration. Kaolinite is a typical 1:1 clay mineral while montmorillonite and vermiculite are 2:1 clays. When aluminum or iron (+3) is substituted for silicon (+4) and magnesium or iron (+2) for aluminum

(+3), a permanent, net negative charge results on the surface of the clay mineral. This negative charge is satisfied by surface retention of a cation such as H^+, K^+, Ca^{2+}, Mg^{2+}, Al^{3+}, etc. The magnitude of the negative charge is measured by determining the cation exchange capacity (CEC), which is commonly expressed in meq/100 g. The CEC arising from isomorphous substitution is not pH dependent. However, clay minerals possess some pH dependent CEC, about 10 percent, arising from the dissociation of hydroxyl groups (–OH) present at the edges of broken clay crystals. The ability of clay minerals to attract and retain cations is a very important characteristic in soils. Soil cation exchange capacity will be discussed later in detail. In addition to CEC, additional properties of clays include a high surface area, the capacity to sorb metals and organics, and the ability to swell or shrink depending on water content.

Other silicate minerals are less important than the clays, primarily because of their minimal CEC and low surface area. Included in this category are minerals such as quartz, feldspars, micas, and amphiboles.

The predominant oxide minerals are compounds of Fe, Al, and Mn. A significant part of the Fe and Al oxides in soils may be present as amorphous rather than crystalline compounds, depending on soil pH, organic matter and other properties. Amorphous compounds possess a higher surface area and greater chemical reactivity than their crystalline counterparts. Recent research indicates that Fe and Al hydrous oxides can sorb Zn^{2+}, Cd^{2+}, and probably other trace metals. It has been well established that Fe and Al compounds in soil are important sites for P fixation. In addition, Fe and Al oxides may interact with clay minerals resulting in the general trend observed for a direct relationship between clay, Fe and Al content of soils. The solubility of Fe^{3+} and Al^{3+} in soils is depressed with increasing pH. Since Fe and Mn can undergo oxidation-reduction reactions, the forms and subsequent solubility of Fe and Mn are controlled by soil aeration.

Carbonates influence the pH and buffering capacity of a soil. Leaching of soils causes the carbonates to dissolve and leach downward. This results in an acidic environment and additional $CaCO_3$ may have to be applied to promote crop growth, or, in the case of sludge application, to maintain a pH above 6.5.

Organic matter is the other major component of soils (i.e., humus). There are two major categories of soil organic matter: the humic and nonhumic substances. Nonhumic substances are the intact or partially degraded compounds from plants, animals, or microbial residues. In general, these substances account for less than 25 percent of soil organic matter. With time, the majority of these compounds decompose and a portion of the degradation products becomes incorporated into humic substances.

Humic substances are a complex, high molecular group of organic compounds that result from chemical and enzymatic reactions of degradation products from plant, animal and microbial residues. Humic substances are subdivided into the following categories: fulvic acid (acid and alkali soluble), humic acid (acid insoluble, alkali soluble), and humin (acid and alkali insoluble). Although quantitative differences exist in chemical composition, all three fractions are characterized by possessing a non-polar (aromatic rings) core with attached polar functional groups. The non-polar nature of humics accounts for the strong affinity of soil organic matter for added organic compounds such as herbicides, pesticides, etc. Functional groups found in soil organic matter include carboxyl (–COOH), phenolic and alcoholic hydroxyl (–OH), amino ($-NH_2$) and sulfhydryl (–SH) groups. All of these functional groups exhibit acid-base character and thus, soil organic matter is involved in the buffering of soil pH. Furthermore, the ionization of functional groups results in soil organic matter possessing a net negative charge or CEC. Soil pH strongly influences the CEC of soil organic matter with increasing pH resulting in increasing CEC. Metals may also interact with functional groups through chelation and ion exchange mechanisms.

Clay minerals and organic matter constitute virtually all soil CEC. The humic fraction of soil organic matter normally ranges between 200–300 meq/100 g, whereas the CEC of clay minerals varies according to the mineral type, between 5–120 meq/100 g. Therefore, the relatively small fraction of organic matter present in a soil may exert a large influence on total CEC. Even though a wide range is encountered for the CEC of individual clay mineral types and soil organic matter, statistical analysis of CEC, clay and organic matter data for soils have resulted in development of an equation to predict CEC from clay and organic matter content.[17]

Nitrogen Transformations

A simplified schematic of the N cycle is shown in figure 9–A–1. Both organic and inorganic nitrogen are added to soils by sludge addition. While the inorganic nitrogen (NH_4^+ and NO_3^-) is readily available for plant uptake, only 15 to 25 percent of the organic nitrogen is converted to available forms the first year after application.[54] The availability then decreases each consecutive year following application.

Ammonium-N is a major N species added to soils in sludge applications. It may be held on the clay surface as an exchangeable cation. In soils containing micaceous minerals, NH_4^+ may penetrate between the mineral plates causing collapse of the mineral and NH_4^+ fixation. This form of NH_4 is relatively inert and will not participate to a great extent in further chemical or microbial reactions. Of most significance, especially when considering surface application of sludges, is NH_3 volatilization. In excess of 50 percent of the NH_4-N is commonly volatilized during air-drying of sewage sludges.[24] The extent of NH_3 volatilization after surface application of sludge will depend on the following factors: (1) soil pH; (2) soil CEC; (3) climate (temperature, relative humidity); and (4) soil conditions (water content, rate of infiltration). Labo-

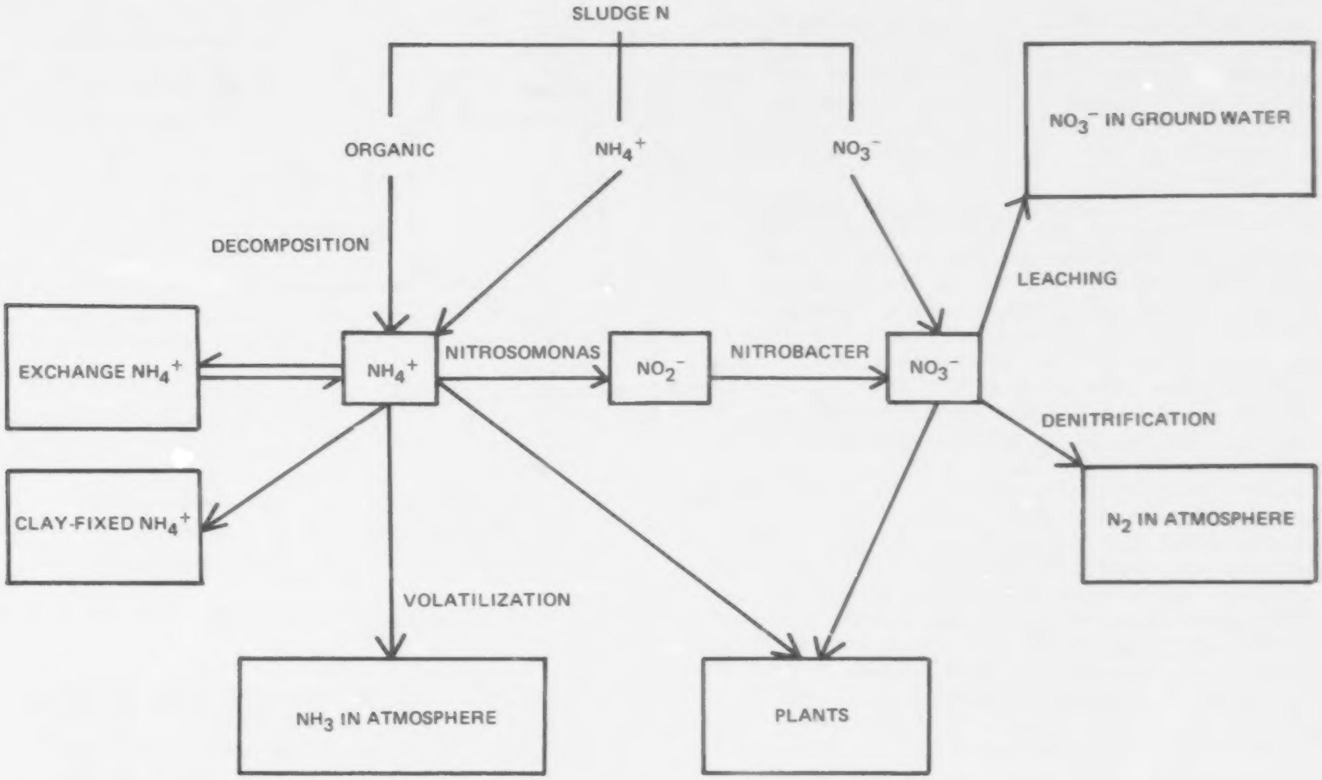

Figure 9–A–1.—Nitrogen cycle in soil.

ratory experiments indicate that the extent of NH_3 volatilization is related inversely to CEC and directly to pH. Volatilization of NH_3 can be reduced to <5 percent of applied NH_4-N by incorporation of sludge into the soil. Unfortunately, quantitative data are not available concerning the magnitude of NH_3 volatilization under field conditions. At present, recommendations based on N application rates assume that 50 percent of the plant available N is lost via NH_3 volatilization when sludge is surface applied.

After addition to soil, essentially all ammonium will be converted to nitrate (NO_3^-). This process, called nitrification, involves two steps. First, NH_4^+ is oxidized to NO_2^- by the bacterium *Nitrosomonas,* followed by oxidation of NO_2^- to NO_3^- by *Nitrobacter*. In neutral soils, essentially all NH_4^+ added will be converted to NO_3^- within 2 to 4 weeks after application. Depressed nitrification rates may occur in sludge amended soils at N application rates approaching 1,000 lbs/acres (1120 kg/ha), amounts in excess of those recommended for most soils. In contrast to NH_4^+ which is held as an exchangeable cation, NO_3^- remains as a soluble anion in the soil solution.

The formation of NO_3^- is significant because NO_3^- can be lost from the soil through leaching. In humid regions, N applied to soils in excess of crop requirements may leach and result in NO_3^- contamination of groundwater. Systems developed for land treatment of wastewater are based on the premise that a growing crop will reduce the NO_3^- concentration in the soil solution to levels acceptable for drinking water. Thus, the annual amount of N applied to soils in sludge is based on the N required by the crop grown.

In addition to leaching, NO_3^- may be lost from soils through denitrification. Denitrification occurs when facultative anaerobic bacteria utilize NO_3^- as a terminal electron acceptor in place of O_2 under anaerobic conditions (i.e., saturated or excessive water contents). In an "aerobic" soil, it is also possible that denitrification can be occurring because the center of soil aggregates may be water-saturated and anaerobic. The end-product of denitrification is generally N_2, which diffuses into the atmosphere. Denitrification may be a significant mechanism for N loss in soils treated with liquid sludge because of localized increases in soil H_2O content. Thus, NH_4^+ may be oxidized to NO_3^- in an aerobic zone followed by diffusion of NO_3^- into anaerobic microsites where denitrification occurs.

The adverse effects of overfertilization of soils with sewage sludge are twofold. First, use of excess N causes luxury consumption of NO_3^- by many plants and results in potential animal health problems when high NO_3^- feedstuffs are consumed and second, NO_3^- can be leached from the soil profile and enter groundwaters. The latter problem is the most significant from a long-term standpoint.

The two areas of concern involving high concentrations of NO_3^- in waters are direct health effects and eutrophication. Nitrate-nitrogen may present a health hazard. Winton et al.[33] described the circumstances which may induce methemoglobinemia or cyanosis in infants. The main controlling factor in this disease is the daily nitrate intake, and hence, the nitrate concentration of drinking water plays an important role. Drinking water standards in the United States mention nitrate concentrations of 45 mg NO_3^-/1, as maximally permissible levels. Also livestock may suffer from a number of symptoms caused by too high nitrate-nitrogen levels in the drinking water like methemoglobinemia, vitamin A deficiency, reproductive difficulties and abortions, and loss of milk production. Increased concentrations of N in water may also cause eutrophication (i.e., nutrient enrichment) of surface water. Eutrophication results in rapid growth of the nuisance aquatic plants. The most commonly known features of eutrophication are phytoplankton blooms. The exact factors responsible for eutrophication are still insufficiently understood, however, P-concentrations below 0.01 mg/l and N concentrations below 0.2–0.3 mg/l appear to minimize algal blooms in surface waters.

Phosphorus Interactions

The behavior of phosphorus in soils is controlled by chemical rather than biological reactions. The interactions of the phosphorus cycle are illustrated in figure 9–A–2. The majority of phosphorus in sludges is present in inorganic compounds, about 70 to 90 percent of total phosphorus. Therefore, even though mineralization of the organic phosphorus occurs during decomposition, inorganic reactions of phosphorus are of greater importance in sludge application.

The P immediately available for plants is present in the soil solution. As plants deplete the soil solution, the equilibria with sorbed P and P minerals are shifted resulting in replenishment of the soluble P pool. The quantity of soluble P in soil is referred to as an "intensity" factor whereas the total amount of P present that may enter the soil solution is a "capacity factor." Thus, the concentration of soluble P in soils may not be related to the ability of a soil to supply P to crops throughout the entire growing season. Soils possess the ability to "fix" P through sorption and/or precipitation reactions. As a result, the concentration of P in the soil solution is generally <0.1 mg/l, resulting in minimal leaching losses of P. In fact, land treatment of wastewaters is based on retention of P as wastewater percolates through a soil profile. Because phosphorus accumulates in the soil surface, phosphorus toxicity may occur following repeated sludge amendments. In most instances, other parameters (e.g., heavy metals) will limit total sludge loadings to a level where P toxicity to crops will not be a problem.

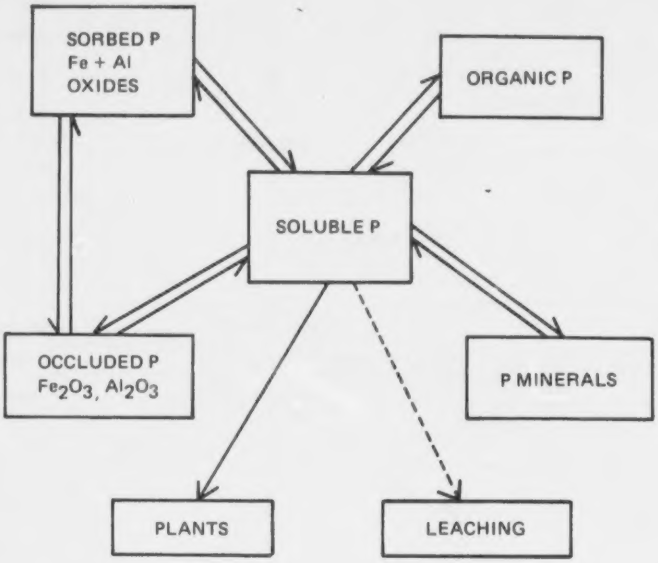

Figure 9–A–2.—Phosphorus cycle in soil.

Serious problems in crop production due to excess phosphorus are rare. It has occasionally been inferred that excess P in the soil impairs plant growth via indirect action. For example, Zn-deficiency symptoms can be traced to P inhibition at the root surface when rather soluble phosphates are present. However, sludge applications add both P and Zn to minimize any potential P-Zn interactions.

Reactions of Metals in Soil

The majority of sludges add appreciable amounts of trace metals to soils. The metal content of soils and plants is quite variable depending on the soil type and plant species. Trace elements such as B, Co, Cu, Mn, Mo, Se and Zn are essential for plant growth; however, if excessive concentrations are applied to soil, metal toxicities may develop and crop yields will decrease. Often times, the interpretation of a metal toxicity to plants is not straightforward because of interactions between nutrients (e.g., P induced Zn deficiency). Non-essential metals (e.g., Cd, Ni, Pb) may be toxic to plants and decrease yields. Of greater concern is the enrichment of food and fiber with metals potentially harmful to humans and animals. Because As, Pb and Hg are not taken up from soils by most plants, the element of greatest concern is Cd. In general, the rationale of sludge application guidelines is to minimize (1) decreased crop yields caused by metal additions to soil; and (2) increased concentrations of non-essential metals (e.g., Cd) in the plant part consumed by man or animals. The fate of sludge metals in soils and plants has been reviewed recently.[47]

The chemistry of metals in soils is quite complex and incompletely understood. The fate of metals added to soils in sewage sludge is depicted in figure 9–A–3. Metals available to plants and susceptible to leaching are present in the soil solution as the free metal ion (M^{2+}), complexes (MOH^+, MCl^+, etc.) and chelates (M-Fulvic acid, etc.). As plant uptake or leaching occurs, the soil solution re-equilibrates with the solid phase, resulting in a relatively constant concentration in the soil solution. The equilibrium concentration will be controlled by soil properties such as pH, E_h, and solution composition. In general, the solubility and plant availability of metals decreases with increasing pH.

Metals in the soil solution are continuously interacting with metals present as precipitates (carbonates, hydroxides, etc.), bound with soil organic matter, sorbed by clay minerals and retained by hydrous oxides. Furthermore, the properties of clay minerals in soil are influenced to a great extent by interaction with organic matter and hydrous oxides. In general, the organic matter present in clay-organic matter complexes is more resistant to decomposition than "free" organic matter resulting in the common trend for the clay and organic matter contents of soils to increase proportionately. The presence of acidic functional groups in soil organic matter is responsible for metal retention through both exchange and chelation mechanisms. Considerable evidence is accumulating concerning the importance of metal retention by Fe and Al hydrous oxides. As shown in figure 9–A–3, hydrous oxides may also be sorbed onto clay minerals but they still retain the ability to sorb metals. The Fe and Al hydrous oxide content of soils also tends to increase with increasing clay content.

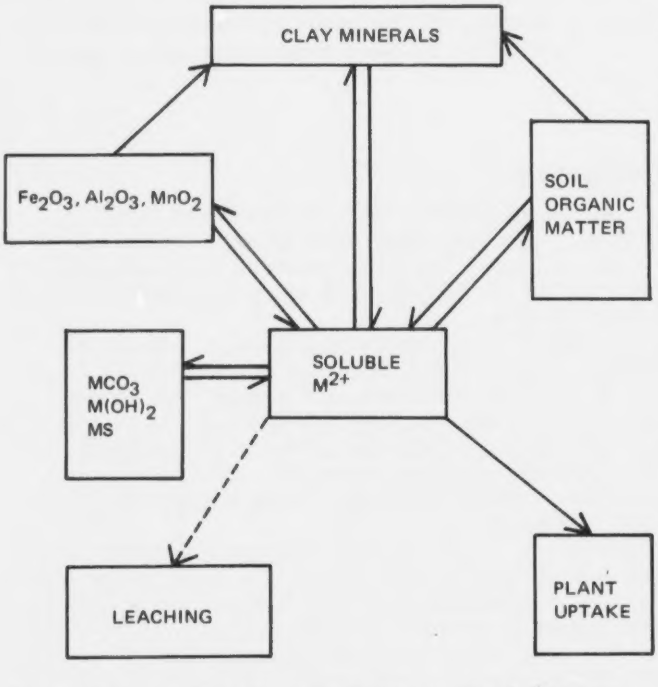

Figure 9–A–3.—Reactions of metals in soil (M^{2+} represents Cu, Zn, Ni, Cd, Pb, etc.).

As a result of these interactions between clay, hydrous oxides, and organic matter, CEC has been used as an index of the metal retention capacity of a soil. This does *not* imply that metals added to soils are retained through an ion exchange mechanism. Metals present in soil as an exchangeable cation are readily available for plant uptake but it has been demonstrated in numerous studies that only a small fraction of metals added to soil are present as an exchangeable ion. The above use of CEC for recommending metal loadings is still open to question.

Plants can selectively accumulate certain of these elements while omitting other elements present in soil solution. Often the interpretation of metal toxicity to plants is complicated because of interactions between certain nutrients (i.e., P induced Zn-deficiency). However, in general, elements that can accumulate in plant tissues causing reduced yields of crops or that pose health hazards to man are the most important.[56] Elements such as As, Co, Hg, Mo, Pb, Se, and V may have some effect on crop yield or health, but at present do not appear to be limiting factors. One of the most serious elements concerning health factors is cadmium,[57] but other elements such as nickel, copper, and zinc may cause serious crop damage. These elements are discussed below.

Cadmium is currently the element of greatest concern as a food chain hazard to humans. Acute toxicity to humans has been reported from consuming acidic foods prepared or served in cadmium-plated containers. The more general alleged hazard to humans, however, is one of chronic toxicity, expressed only after long exposure.

An annual loading rate for cadmium on soils has been set at 2 lb/acre·yr (2.24 kg/ha/yr). This value is based on research by Keeney et al.,[17] where additions of 2 lb/acre (2.24 kg/ha) did not significantly increase the concentration of cadmium in corn grain (table 9–A–1). Higher additions of cadmium to the soil did show accumulations of this metal in the plant tissue. A recent analysis by Pahren et al.[57] recommended using 0.9 lb Cd/acre/yr (1.0 kg/ha/yr) as a maximum value for swiss chard. This plant is a heavy metal accumulator and was used as an "indicator" for maximum uptake by a crop. This report suggests that crops previously assumed "not suited" for growth on sludge-amended soils, such as swiss chard and other leafy vegetables, may be used with some constraints on the cadmium in severe sludge and would pose no more a hazard to the national diet than foods naturally high in cadmium such as shellfish. This presumes that foods enter a marketing system where products from many parts of the country are mixed during distribution to retail grocery outlets.

Table 9–A–1.—Cadmium uptake by crops from application of sewage sludge

Year of		Crop[a]	Rate of sludge application, tons/acre[b] (Cd conc. in crop (mg/kg))					
Application	Harvest		0	2	4	8	16	32
1971	1972	Rye	0.10	0.25	0.30	0.25	0.30	0.30
	1972	Corn	0.09	0.09	0.13	0.08	0.11	0.09
	1973	Corn	0.06	0.05	0.05	0.08	0.05	0.05
1972	1973	Rye	0.23	0.25	0.35	0.45	0.40	0.50
	1973	Corn	0.08	0.06	0.07	0.07	0.02	0.05
	1974	Corn	0.07	0.07	0.07	0.07	0.07	0.19
1973	1973	Sorghum-Sudan	0.53	0.50	0.75	0.75	0.85	0.95
	1974	Corn	0.07	0.07	0.07	0.07	0.07	0.12

[a] Refers to rye and sorghum-sudan forage and corn grain.

[b] Application of 0, 2, 4, 8, 16 and 32 tons/acre added 0, 0.28, 0.56, 1.12, 2.24 and 4.48 lbs Cd/acre, respectively.

Zinc constitutes an essential element for animals and plants. However, zinc toxicity in plants has also been reported, though only at relatively high concentrations. Zinc toxicity is usually caused by interactions with other essential elements like phosphorus and iron.

Phytotoxic levels of Zn are at about 400 ppm and up, and toxicity in animals starts when the Zn content of the diet exceeds roughly 1,000 ppm. Most plants are severely injured at such high Zn levels.[58] Therefore, lower toxicity levels of plants as compared to animals serve as protection against Zn accumulation in the food chain. One of the major factors controlling Zn availability is the pH. For the same Zn addition level the yield reduction and the zinc contents of swiss chard leaves were found to be much higher at pH 5.3 than at pH 6.4.[59]

Except for certain accumulator species, plants are excellent biological barriers for heavy metals.[60] That is notably true for nickel, copper, and lead. An exception to the plant barrier rule is the potential for toxicity to ruminants consuming forages with a low ratio of molybdenum to copper.[61] Molybdenum accumulation in soils from sludge application and subsequent increases in forage molybdenum content is a potential hazard to grazing ruminants, especially where soils are neutral or alkaline.

With lead, nickel, and copper, the root provides the barrier since uptake and, especially, translocation are low. Baumhardt and Welch have shown a significant but small increase of lead in corn stover from lead acetate applications to soil (3,200 kg/ha) although the corn grain content was only 0.4 mg/kg of lead and not affected by application rate.[62] No evidence of phytotoxicity was observed. Numerous other studies have shown minimal plant uptake of lead from soils amended with sewage sludge.[36]

Nickel and copper have the added protective mechanism of phototoxicity at low plant concentrations. Copper and nickel concentrations of 30 and 25 mg/kg, respectively, are believed to be phytotoxic.[73] Thus, not only is uptake and translocation of these elements low but the plant dies or fails to grow long before it can accumulate a metal content toxic to a mammalian consumer.

At present, there is considerable disagreement among researchers concerning the impact of annual versus total metal loadings. Data exist to show that only the first addition exerts a significant impact on cadmium in plant tissues. The current approach used by EPA in the technical bulletin is used herein.[23]

The life of an agricultural disposal site is based on the total amounts of lead, copper, nickel, zinc, and cadmium applied to the soil.[58] These limits are designed to allow growth, and use of crops at any future date and stipulates soil pH ≥ 6.5. Metal toxicities and/or contamination of the crops may occur due to increasing metal availability if soils are not maintained at pH ≥ 6.5. Suggested metal limits are shown in table 9–14. The total metal additions shown in table 9–14 are the best available estimates. However, these values are not "the last word," and will be revised based on research data that is being collected. Furthermore, the establishment of standards for metals in crops by FDA will allow one to establish the appropriate metal limits for agricultural soils. The rationale of sludge application guidelines is to minimize (1) decreased crop yields caused by metal additions to soil; and (2) increased concentrations of nonessential metals in the plant parts consumed by man or animals.

Pathogens

Although the general health of the United States is relatively good, the wastes from people infected with disease organisms are also introduced into a sewage system. Most of the organisms are subsequently found in sewage sludges.

A large variety of disease organisms is present in sewage sludges. These include protozoa, parasitic worms, pathogenic bacteria, and viruses. The numbers and kinds of pathogenic organisms present in sludges are quite variable, depending primarily on the health of the community. However, there are usually sufficient pathogenic organisms present in raw sludges to warrant public health concerns.

Only a few of the hundreds of disease organisms have high enough survival rates in soil and water to warrant concern. The organisms of most concern are: *Ascaris lumbricoides, Entamoeba histolytica,* other parasites, *Salmonella typhi,* other *Salmonella* species, *Shigella sp., Vibrio cholera,* certain other bacteria, and some viruses. A brief description of each is presented below.

Parasites and Protozoa

Relatively little is known about the possibility of parasitic disease transmission via sludge amended soils. Parasitic ova and cysts generally are quite resistant to sludge digestion, disinfectants, and adverse environmental conditions. Many, in fact, require a period of free living existence in the soil to develop infectiousness for man. While often thought of as "tropical diseases" many of these pathogens are of cosmopolitan distributions and commonplace within the United States.

The intestinal protozoan parasite, *Entamoeba histolytica*, causes amoebic dysentery and produces cysts that are voided in the feces of infected individuals. However, cysts are apparently unable to survive anaerobic digestion, even at low temperatures, and are destroyed within 3 days on vegetable surfaces.[66] Under optimum conditions of temperature and moisture they survive 6–8 days in soils.[67]

The intestinal nematodes (roundworms) and cestodes (tapeworms) are probably of greater public health significance than the protozoan agents in terms of sludge disposal.

Among the intestinal parasites, *Ascaris lumbricoides*, a roundworm or nematode, is most frequently mentioned as a potential problem in human health. The eggs or ova of this pest are excreted in the feces of infested individuals and have been shown to survive sewage treatment, including anaerobic digestion. The ova are quite resistant to destruction and may persist in soil for several years. The ova must be ingested in order to parasitize.[68]

Since a portion of animal wastes reach municipal sludges, parasites of animal origin are also of concern. Two zoonotic roundworms, *Toxacara canis* and *T. cati*, are nearly universal in our pet population and have a life cycle in their normal host identical to Ascaris in man. When ingested by a child these worms are unable to complete their normal developmental cycle and continue to wander through the tissues for prolonged periods before eventually succumbing. This results in a chronic and usually mild disease (visceral larva migrans) lasting up to a year. Occasionally, more serious manifestations are seen, and the larvae are particularly dangerous if they enter the eye since blindness may result.[57]

The parasites considered potential problems in sludge management are outlined in table 9–A–2.

Bacteria

Bacteria are apparently the most fragile of the three groups of pathogens. The survival of bacteria in soil is

Table 9–A–2.—Parasites of concern for possible transmission via sludge amended soils[57]

Organism	Disease	Reservoir(s)	Range(s)
Protozoa			
Balantidium coli	Balantidiasis	Man, swine	Worldwide
Entamoeba histolytica	Amebiasis	Man	Worldwide[b]
Giardia lamblia	Giardiasis	Man, animals	Worldwide
Toxoplasma gondii	Toxoplasmosis	Cat, mammals, birds	Worldwide
Nematodes (Roundworms)			
Ascaris lumbricoides	Ascariasis	Man, swine	Worldwide—Southeastern USA[b]
Ancylostoma duodenale[a]	Hookworm	Man	Tropical—Southern USA[c]
Necator americanus[a]	Hookworm	Man	Tropical—Southern USA[c]
Ancylostoma braziliense (cat hookworm)	Cutaneous Larva Migrans	Cat	Southeastern USA
Ancylostoma caninum (dog hookworm)	Cutaneous Larva Migrans	Dog	Southeastern USA
Enterobius vermicularis (pinworm)	Enterobiasis	Man	Worldwide[b]
Stronglyoides stercoralis (threadworm)[a]	Strongyloidiasis	Man, dog	Tropical—Southern USA[b]
Toxocara cati (cat roundworm)	Visceral Larva Migrans	Canivores	Probably worldwide
Toxocara canis (dog roundworm)	Visceral Larva Migrans	Canivores	Sporadic in USA
Trichuris trichiura (whipworm)	Trichuriasis	Man	Worldwide[b]
Cestodes (Tapeworms)			
Taenia saginata (beef tapeworm)	Taeniasis	Man	Worldwide—USA
Taenia solium (pork tapeworm)	Taeniasis	Man	Rare in USA
Hymenolepis nana (dwarf tapeworm)	Taeniasis	Man, rat	Worldwide[b]
Echinococcus granulosus (dog tapeworm)	Hydatid Disease	Dog	Far North-Alaska
Echinococcus multilocularis	Aleveolar Hydatid Disease	Dog, canivores	Rare in USA

[a] Man infested via skin contact.
[b] Has been identified in domestic sludges.
[c] Reported in foreign sludges only to date.

reduced by sunlight, drying, and other factors when sludge is applied to land. Contamination of plants can occur by direct contact and rain splashes, but survival for an infective dose is usually short (a few weeks). Bacteria can survive longer when protected from sunlight or desiccation.

Typhoid and paratyphoid fevers are caused by *Salmonella typhi* and *S. paratyphi*, respectively. These fevers usually result from consumption of contaminated drinking waters. However, food may be contaminated either directly or by a carrier individual, or indirectly by contaminated waters used for irrigation of fresh vegetables. Fortunately, the incidence of this disease in the United States is very low.[69]

The incidence of salmonellosis, other than typhoid fever, is much greater. This disease, caused by a number of species of *Salmonella*, is characterized by diarrhea, abdominal pain, and vomiting. Its predominant cause is due to *S. typhimurium*. Many cases of salmonellosis are not reported because the symptoms may be very short lived, or very mild, but the incidence is believed to be about 2 million cases per year.[40]

Shigellosis, also known as bacillary dysentery, is caused primarily by *S. sonnei* and *S. flexneri*. This is an intestinal disease of man, and can spread rapidly from person to person under improper sanitary conditions. This organism is mainly transmitted via the water route and does not survive long in the hostile environment of the soil.

Cholera is caused by *Vibrio cholera*. The incidence of waterborne outbreaks of cholera outside the United States is numerous. However, there has been virtually no reported cases of cholera in the United States for many years.[55] Therefore, the likelihood of cholera from sludges in the United States is minimal.

Another class of bacterial diseases generally found only in injured or weak individuals, include enteric infections with strains of *Escherichia coli, Pseudomonas aeruginosa*, and *Klebsiella sp*. These pathogens can occur in human wastes and are at least potential hazards in sludges.[55]

Viruses

Viruses may persist in soils and on vegetation for several weeks or months. If exposed to sunlight or desiccation, viruses will eventually be inactivated. Most enterovirus infections occur early in life and are mild when evident. The majority of such infections usually are entirely subclinical. For man, the virus of greatest potential concern appears to be Hepatitis A. This is a serious disease which has an appreciable potential for long-term liver damage.

The other viruses found in wastes would include members of the Coxsakie, Echo, Adeno, and Reovirus groups. These produce a variety of diseases including aseptic meningitis, myocarditis, respiratory involvement and gastrointestinal upset.

A considerable amount of research has been conducted recently on viral survival and movement through soils from sewage wastewaters and sludges. It is generally believed that chlorination is more effective in eliminating bacteria than viruses,[71] but anaerobic digestion does inactivate many viral particles.[72] Even though viral particles are adsorbed by soil particles, it is believed they are still viable and may cause infection.

Controlling Vector Spread of Pathogens

The presence of pathogenic organisms is partially responsible for discouraging sludge applications on soils where vegetables are grown. Since most pathogens of concern do not survive for extended time periods in soils, vegetables can be grown in sludge amended soils as long as a rest period is provided. The application of raw, undigested sludge to the soil surface is not recommended not only because of potential contamination of crops but also because of odor and other aesthetic problems. However, raw sludges are amenable to subsurface (injection) application without undue environmental concerns. Obviously, vegetables, especially root crops, should not be grown in such cases. Caution is advisable when sprinkler irrigation is used for sludge application. The major concerns are surface contamination of crops and potential spread of pathogens through formation of aerosols and subsequent drift to adjacent areas. Sprinkler irrigation of sludges requires more management to minimize potential problems than other application systems.

In summary, although questions arise concerning the impact of pathogens in land disposal systems, the lack of problems encountered by the numerous ongoing projects using land application of sludges suggests that pathogens are a potential problem only and that vector spread has been minimal.

Organics

The concentration of organics, such as chlorinated hydrocarbon pesticides and polychlorinated biphenyls (PCB's), can be elevated above background levels (<10 ppm) in sewage sludges from cities receiving wastes from industrial discharges of these organic compounds. The potential impact of organic compounds on land application practices has been discussed recently by Pahren et al.[57] and Jelinek and Broude.[65] Very little research has been conducted on the uptake of organics by crops growing on sludge treated soils so the following discussion emphasizes data obtained from related experiments. Pesticide and PCB levels in sludges are indicated in table 9–A–3.

In general, a minimal amount of pesticides is sorbed by plants and translocated to aerial pacts. For example, the foliage of corn contains ≤ 3 percent of the Dieldrin applied to soil while the concentration in the roots was appreciably greater. Nearly all pesticides are relatively non-polar molecules which are strongly bound by soil organic matter and are, undoubtedly, likewise bound to

Table 9–A-3.—Pesticide and PCB content of dry sludges[a]

Compound	Range (mg/kg)		Number of sludges examined
	Minimum	Maximum	
Aldrin[b]	ND[c]	16.2	5
Dieldrin[d]	<0.03	2.2	21
Chlordane[b]	3.0	32.2	7
DDT + DDD[b]	0.1	1.1	7
PCB's[e]	ND[3]	352.0	83

[a] From Pahren et al.[57]
[b] Examined in 1971.
[c] Nondetectable.
[d] Examined in 1971, 1972, 1973.
[e] Examined in 1971, 1972, 1973, 1975.

the surface of plant roots. Thus, the concentration of pesticides in root tissue may not result from typical uptake mechanisms where the molecule must permeate the membranes of root cells.

The uptake of PCB's has been evaluated using carrots as the test crop.[74] Soils treated with Aroclor 1254 at 100 mg/kg produced carrots containing from 2–30 mg PCB/kg, depending upon the examined component of the PCB mixture. More significantly, 97 percent of the PCB residue was found in carrot root peelings, which constituted only 14 percent of the carrot weight. These results suggest that PCB's are not actually taken up by carrots but rather they are physically adsorbed on the surface of carrot roots. Furthermore, carrots have been used in several studies as "scavengers" for organochlorine pesticides in soils. Additional evidence supporting the inability of plants to accumulate organics was obtained by Jacobs et al.,[75] who grew orchardgrass and carrots in soils treated with 10 and 100 mg/kg of polybrominated biphenyls (PBB's). At these rates of PBB addition, the amount of uptake was essentially nondetectable (20–40 μg/kg) in carrots and nondetectable in orchardgrass. It should be emphasized that the rates used in these studies far exceeds those expected from sludge application. In general, plants possess the ability to exclude the majority of organics added to soils, resulting in minimal impact on the quality of forages and grains. Furthermore, even though PCB's and related compounds resist microbial degradation, they are slowly decomposed after incorporation in soils.

A potential problem arising from organics in sludge is direct ingestion by animals grazing on forages treated with a surface application of sludge. Most organics are concentrated in tissues (fats) and fluids (milk). Even though a rain will remove the majority of sludge adhering to forages after a surface application of sludge, a sufficient amount of sludge may remain resulting in direct ingestion of organics by cattle. For this reason, Pahren et al.[57] suggested that sludges surface applied to grazed forages contain ≤ 10 mg/kg of PCB's. This problem can be eliminated for sludges containing >10 mg/kg PCB by incorporation of the sludge prior to planting forages.

An estimate of the potential impact can be made by assuming that sludge will be applied to 5 tons/acre to satisfy the N needs of a crop. The FDA tolerance limit for PCB's in infant foods is 0.2 mg/kg. If we use this as the maximum concentration in soils (i.e., soil could be consumed as food), a concentration of 40 mg/kg of PCB's would be allowable in sludge.

Appendix B: SOIL TESTING

Soil testing is utilized extensively in agriculture, and to a limited extent in forestry to assess the ability of a soil to supply N, P, K and trace elements to plants.[22] In addition, plants vary in their ability to tolerate acid conditions so soil pH and lime requirement are routinely determined. Because a reliable soil test for plant available N does not exist, P and K are the principal plant nutrients determined in soils. The approach used in soil testing is to determine the amount of P or K extracted from soil with a specific reagent. Knowing the relationship between crop yield and nutrient concentration in the soil, it is possible to recommend the amount of fertilizer required to attain a specific yield. With increasing levels of a nutrient in soil, both yield and concentration of the element in plant tissue increases. Crop yield will plateau and, for some elements (e.g., metals), decrease when increasing amounts of an element are added to soil. Although yields do change at high (subtoxic) rates of nutrient addition, the concentration in plant tissues may continually increase. The concentration of elements in plant tissues can be used, in most cases, to assess both deficiencies and toxicities.

Development of soil testing procedures involves evaluating a range of extractants and soils in greenhouse and/or field experiments with a particular crop. The extractant showing the best correlation with plant yields and/or composition is used as a soil test. Walsh and Beaton[87] present additional information about the approaches used in soil and plant testing.

Regional variations in soil properties have led to the development of P soil tests for different parts of the U.S. For the sake of brevity, soil tests for P will be subdivided on the basis of calcareous and acid soils. The following extractants are commonly used to evaluate available P in soils:

Calcareous soils — 0.5 M $NaHCO_3$
Acid soils — 0.025 N HC1 + 0.03 N NH_4F (Bray P_1)
— 0.05 N HC1 + 0.025 N H_2SO_4

The similarities of K reactions in acid and calcareous soils result in the majority of states using 1 N NH_4 acetate (pH 7) as an extractant for plant available K. Recommendations for fertilizer P and K applications tend to vary from region to region because yield potentials depend on soil, crop and climatic factors.

Soil tests are also used to assess the availability of Ca, Mg, S, B, and trace elements. Plant available Ca and Mg are extracted with 1 N NH_4 acetate, S with water or $Ca(H_2PO_4)_2$, and Zn, Cu, Mn and Fe with numerous salts, acids or chelating agents. A procedure used in many of the western states employs DTPA (diethylenetriaminepentacetic acid) buffered at pH 7.3 as an extractant for plant available Fe, Zn, Cu and Mn.[76] For sludge amended soils, the major concern is accumulation of excessive metals rather than detecting deficiencies. Nevertheless, the DTPA procedure may also serve as a technique for evaluating plant available metals in soils treated with sludges over a period of years.

A soil property routinely determined in soil testing and one that is essential for soils receiving sludge is the determination of soil pH and lime requirement. Soil acidity results from the presence of free H^+ and exchangeable H^+ and Al^{3+}. Acidity is generated when exchangeable Al^{3+} is displaced by another cation:

$$X\ Al^{3+} + 3K^+ + 3H_2O \qquad 3XK^+ + Al(OH)_3 + 3H{:}8\ 4 +$$

where X represents an exchange site on a clay mineral or soil organic matter. In addition, the dissociation constants for soil organic matter cover a broad range for a given functional group resulting in a large buffering capacity. Hence, measurement of soil pH in H_2O followed by a simple calculation of the amount of $CaCO_3$ needed to reach a desired pH is not valid in soils. Current methods for obtaining lime requirements are based on measuring pH in water (or a dilute salt solution) and in a buffer solution to estimate the buffering capacity of a soil. The extent of pH depression of the buffer caused by adding soil is proportional to the amount of lime needed. The SMP buffer is used by many laboratories and contains p-nitrophenol, K_2CrO_4, $CaCl_2$, Ca acetate, triethanolamine and H_2O (pH 7.5). The buffer method is described in detail by McLean.[77] The relationship between soil + buffer pH and lime requirement is shown in table 9–B–1. Soil pH must be maintained at 6.5 or above in soils treated with sludge so determination of lime requirement is essential. For more detail, the Soil Science Society of America has available a standard soils analysis text.[78]

Table 9–B–1.—Amount of lime ($CaCO_3$) required to adjust mineral soils to pH 6.5[77]

Soil pH determined in SMP buffer	Lime required for soil pH 6.5[a] (tons/acre)
7.0	0
6.8	1.0
6.6	2.4
6.4	3.9
6.2	5.3
6.0	6.7
5.8	8.1
5.6	9.6
5.4	11.1
5.2	12.5
5.0	14.0
4.8	15.5

[a] Applies to mineral soils only.

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Chapter 10

Sludge Landfilling

INTRODUCTION

Sludge landfilling can be generally defined as the burying of sludge; i.e., the application of sludge to the land and subsequent interment by applying a layer of cover soil atop the sludge. To be defined as a landfill, the sludge must be covered by a soil depth greater than that of the plow zone. Therefore, subsurface injection of sludge is a landspreading, not a landfilling operation.

This chapter provides general guidance and a source of information to be used in the design of a landfill receiving municipal wastewater treatment plant sludge. Major alternative sludge landfilling methods are identified and described. Guidance is given on the selection of a landfilling method which is best suited for a given combination of sludge characteristics and site conditions. The design of a sludge landfill is described. Typical costs are presented. A case study and a design example are included.

LANDFILLING METHODS

Suitability of Sludge for Landfilling

In determining the suitability of sludge for landfilling, a determination should be made of the sludge sources and treatment. Analyses should also be performed on the sludge to determine relevant characteristics. This information is needed in order that a full assessment can be made of its suitability for landfilling. Not all wastewater treatment sludges are suitable for landfilling, due to pathogen, odor, or operational problems. An assessment of the suitability of various sludge types has been included as table 10–1.

As shown, only dewatered sludges (having solids contents greater than or equal to 15 percent) are suitable for disposal in sludge-only landfills. Sludges having solids contents less than 15 percent usually will not support cover material. Obviously, the addition of soil to a low-solids sludge may act as a bulking agent and produce a sludge suitable for disposal at sludge-only landfills. However, soil bulking operations are generally not cost-effective on sludges with solids less than 15 percent. Further dewatering should be performed at the treatment plant if sludge-only landfilling is the disposal option selected. Low-solids sludge (having solids contents as low as 3 percent) are suitable for codisposal landfilling. However, sludge moisture should not exceed the absorptive capacity of refuse at a codisposal landfill. Accordingly, low-solids sludge should be received at such sites only if it constitutes a small percentage of the total waste landfilled.

Generally, only stabilized sludges are recommended for landfilling and some degree of stabilization should occur if landfilling is the selected disposal option. However, since stabilization is not required in all States, suggested procedures for landfilling such sludges are described.

The following section describes handling and operating practices for typical sludges. Sludge ash as well as other wastewater treatment plant solids such as screenings, grit, and skimmings require special handling and operating practices.

Sludge Landfilling Methods

The several alternative methods and sub-methods for sludge landfilling include:

1. Sludge-only trench: narrow trench; wide trench.
2. Sludge-only area fill: area fill mound; area fill layer; diked containment.
3. Codisposal: sludge/refuse mixture; sludge/soil mixture.

In this section, each method will be defined and subsequently described in terms of sludge and site conditions specific to that method. In addition, design criteria are identified for each method. The criteria suggested for each method are based on experiences at numerous sludge landfills which embrace a broad range of sludge and site conditions. These criteria should be valid for the vast majority of sludge landfill applications. However, design criteria should be qualified as being "typical" or "recommended." Variations are employed and may be appropriate in some cases. For example, the range of sludge solids contents recommended for each method in this section may vary somewhat depending on the sludge source, treatment, and characteristics. Specifically, a sludge treated with polymers is more slippery and less stable; consequently it will require a higher solids content to be landfilled in the same manner as a sludge not treated with polymers. Nevertheless, the criteria suggested by this section can serve as a starting point. It is recommended that pilot-scale testing be performed to ensure that an operation based on the criteria will function properly for a given sludge and site.

Sludge-Only Trench

For sludge-only trenches, subsurface excavation is required so that sludge can be placed entirely below the

Table 10–1.—Suitability of sludges for landfilling

Process	Feed	Sludge-only landfilling		Codisposal landfilling	
		Suitability	Reason	Suitability	Reason
Thickening					
Gravity	Primary	NS	P,OD,OP	NS	P,OD,OP
	WAS	NS	P,OD,OP	NS	P,OD,OP
	Primary and WAS	NS	P,OD,OP	NS	P,OD,OP
	Digested primary	NS	OP	MS	OP
	Digested primary and WAS	NS	OP	MS	OP
Flotation	Primary and WAS	NS	P,OD,OP	NS	P,OD,OP
	WAS with chemicals	NS	OP	NS	P,OD,OP
	WAS without chemicals NS	NS	P,OD,OP	NS	P,OD,OP
Treatment					
Aerobic digestion	Primary, thickened	NS	OP	MS	OP
	Primary and WAS, thickened	NS	OP	MS	OP
Anaerobic digestion	Primary, thickened		OP	MS	OP
	Primary and WAS, thickened	NS	OP	MS	OP
Incineration	Primary, dewatered	S	—	S	—
	Primary and WAS, dewatered	S	—	S	—
Wet oxidation	Primary or primary and WAS	NS	OD,OP	MS	OD,OP
Meat	Any, thickened	NS	OD,OP	MS	OD,OP
Lime stabilization	Primary, thickened	NS	OP	MS	OP
	Primary and WAS, thickened	NS	OP	MS	OP
Dewatering					
Drying beds	Any, digested	S	—	S	—
	Any, lime stabilization	S	—	S	—
Vacuum filter	Primary, lime conditioned	S	—	S	—
	Digested, lime conditioned	S	—	S	—
Pressure filtration	Digested, lime conditioned	S	—	S	—
Centrifugation	Digested	S	—	S	—
	Digested, lime conditioned	S	—	S	—
Heat drying	Digested	S	—	S	—

WAS = Waste activated sludge.
NS = Not suitable.
MS = Marginally suitable.
S = Suitable.
P = Pathogen problems.
OD = Odor problems.
OP = Operational problems.

original ground surface. Trench applications require that groundwater and bedrock be sufficiently deep so as to allow excavation and still maintain sufficient buffer soils between the bottom of sludge deposits and the top of groundwater or bedrock.

In trench applications, soil is used only for cover and is not used as a sludge bulking agent. The sludge is usually dumped directly into the trench from haul vehicles. On-site equipment is normally used only for trench excavation and cover application; it is not normally used to haul, push, layer, mound, or otherwise come into contact with the sludge.

Although in some cases cover application may be less frequent, cover is normally applied over sludge the same day that it is received. Because of the frequency of cover, odor control is optimized; therefore, trench is more appropriate for unstabilized or low-stabilized sludges than other landfilling methods. The soil excavated during trench construction provides quantities which are almost always sufficient for cover applications. Accordingly, soil importation is seldom required in trench applications.

Two sub-methods have been identified under trench applications. These include (1) narrow trench and (2) wide trench. Narrow trenches are defined as having widths less than 10 ft (3.0 m); wide trenches are defined as having widths greater than 10 ft (3.0 m). The depth and length of both narrow and wide trenches are variable and dependent upon a number of factors. Trench depth is a function of (1) depth to groundwater and bedrock, (2) sidewall stability, and (3) equipment limitations. Trench length is virtually unlimited, but inevitably dependent upon property boundaries and other site conditions. In addition, trench length may be limited by the need to discontinue the trench for a short distance or place a dike within the trench to contain a low-solids sludge and prevent it from flowing throughout the trench.

Narrow Trench

As stated previously, a narrow trench has a width of less than 10 ft (3.0 m). Sludge is usually disposed in a single application and a single layer of cover soil is applied atop this sludge. Narrow trenches are usually excavated by equipment based on solid ground adjacent to the trench and equipment does not enter the excavation. Accordingly, backhoes, excavators, and trenching machines are particularly useful in narrow trench operations. Excavated material is usually immediately applied as cover over an adjacent sludge-filled trench. However, occasionally, it is stockpiled alongside the trench from which it was excavated for subsequent application as cover over the trench. Cover material is then applied by equipment also based on solid ground outside of the trench. Relevant sludge and site conditions as well as design criteria are presented in the following tabulation.

Sludge and Site Conditions

Sludge solids content	15–20 percent for 2–3 ft (0.6–0.9 m) widths 20–28 percent for 3–10 ft (0.9–3.0 m) widths
Sludge characteristics	unstabilized or stabilized
Hydrogeology	deep groundwater and bedrock
Ground slopes	<20 percent

Design Criteria

Trench width	2–10 ft (0.6–3.0 m)
Bulking required	no
Cover soil required	yes
Cover soil thickness	3–4 ft (0.9–1.2 m)
Imported soil required	no
Sludge application rate	1,200–5,600 yd^3/acre (2,300–10,600 m^3/ha)
Equipment	backhoe with loader, excavator, trenching machine

The main advantage of a narrow trench is its ability to handle sludge with a relatively low solids content. As shown, a 2 to 3 ft (0.6 to 0.9 m) width is required for sludge with a solids content between 15 and 20 percent. Normally, soil applied as cover over sludge of such low solids would sink to the bottom of the sludge. However, because of the narrowness of the trench, the soil cover bridges over the sludge, receiving support from solid ground on either side of the trench. In this operation cover is usually applied in a 2 to 3 ft (0.6 to 0.9 m) thickness.

A 3 to 10 ft (0.9 to 3.0 m) width is more appropriate for sludge with solids contents from 20 to 28 percent. At this width, the bridging effect of the cover soil is non-existent. However, the solids content is high enough to support cover. In this operation, cover is usually applied in a 3 to 4 ft (0.9 to 1.2 m) thickness and dropped from a minimum height to minimize the amount of soil that sinks into sludge deposits.

The main disadvantage of narrow trench operations is that it is relatively land-intensive. As shown above, typical sludge application rates in actual fill areas (including inter-trench areas) range from 1,200 to 5,600 yd^3/acre (2,300 to 10,600 m^3/ha). Generally, application rates for narrow trenches are less than for other methods. Another drawback with narrow trench operations is that liners are impractical to install.

Wide Trench

As stated previously, a wide trench has a width of greater than 10 ft (3.0 m). Wide trenches are usually excavated by equipment operating inside the trench. Accordingly, track loaders, draglines, scrapers, and track dozers are particularly useful in wide trench operations. Excavated material is usually stockpiled on solid ground adjacent to the trench from which it was excavated for subsequent application as cover over that trench. However, occasionally it is immediately applied as cover over an adjacent sludge-filled trench. Relevant sludge and site conditions as well as design criteria are presented in the following tabulation.

Sludge and Site Conditions

Sludge solids content	20–28 percent for land-based equipment ≥28 percent for sludge-based equipment
Sludge characteristics	unstabilized or stabilized
Hydrogeology	deep groundwater and bedrock
Ground slopes	<10 percent

Design Criteria

Trench width	>10 ft (3.0 m)
Bulking required	no
Cover soil required	yes
Cover soil thickness	3–4 ft (0.9–1.2 m) for land-based equipment 4–5 ft (1.2–1.5 m) for sludge-based equipment
Imported soil required	no
Sludge application	3,200–14,500 yd^3/acre (6,000–27,400 m^3/ha)
Equipment	track loader, dragline, scraper, track dozer

As shown, cover material may be applied to wide trenches in either of two different ways. If its solids content is from 20 to 28 percent, the sludge in the trench is incapable of supporting equipment. Therefore, cover should be applied in a 3 to 4 ft (0.9 to 1.2 m) thickness by equipment based on solid undisturbed ground adjacent to the trench. In this way, a wide trench may be only slightly more than 10 ft (3.0 m) wide (if a front-end loader is used to apply cover) or up to 50 ft (15 m) wide (if a dragline is used to apply cover). Alternatively, if its solids content is 28 percent or more covered sludge in the trench is capable of supporting equipment. Therefore, cover should be applied by equipment which proceeds out over the sludge pushing a 4 to 5 ft (1.2 to 1.5 m) thickness of cover before it. Track dozers are the most useful piece of equipment in this application.

As for narrow trenches, wide trenches should be oriented parallel to one another to minimize inter-trench areas. Distances between trenches should be only large enough so as to provide sidewall stability as well as adequate space for soil stockpiles, operating equipment, and haul vehicles.

One advantage of a wide trench is that it is less land-intensive than narrow trenches. Typical sludge application rates range from 3,200 to 14,500 yd^3/acre (6,000 to 27,400 m^3/ha). Another advantage of a wide trench is that liners can be installed to contain sludge moisture and protect the groundwater. Therefore, excavation may proceed closer to bedrock or groundwater in wide trenches with liners than in narrow trenches without such protection.

One disadvantage of a wide trench is a need for a higher solids sludge, with solids contents at 20 percent and above. It should be noted that sludges with a solids content of 32 percent or more will not spread out evenly in a trench when dumped from atop the trench sidewall. If wide trenches are used for such high solids sludge, haul vehicles should enter the trench and dump the sludge directly onto the trench floor. Another disadvantage of a wide trench is its need for flatter terrain than that used for narrow trenches. For wide trench applications with sludge up to 32 percent solids, sludge is dumped from above and spreads out evenly within the trench. Accordingly, the trench floor should be nearly level, and this can be more easily effected when located in low relief areas.

Sludge-Only Area Fill

For sludge-only area fills, sludge is usually placed above the original ground surface. Because excavation is not required and sludge is not placed below the surface, area fill applications are particularly useful in areas with shallow groundwater or bedrock. The solids content of sludge as received is not necessarily limited. However, because the sidewall containment (available in a trench) is lacking and equipment must be supported atop the sludge in most area fills, sludge stability and bearing capacity must be relatively good. To achieve these qualities, soil is usually mixed with the sludge as a bulking agent. Since excavation is not usually performed in the landfilling area, and since shallow groundwater or bedrock may prevail, large quantities of soil required usually must be imported from off-site or hauled from other locations on-site.

Because filling proceeds above the ground surface, liners can be more readily installed at area fill operations than at trench operations. Of course, because of the likely proximity of groundwater or bedrock to the ground surface, the installation of a liner will often be required at area fills. With or without liners, surface runoff of moisture from the sludge and contaminated rainwater should be expected in greater quantities at area fills, and appropriate surface drainage control facilities should be considered.

In area fills, the landfilling area usually consists of several consecutive lifts or applications of sludge/soil mixture and cover soil. As for any landfill, cover should be applied atop all sludge applications. However, this cover often is applied as necessary to provide stability for additional lifts. Because some time may lapse between consecutive sludge applications, daily cover is usually not provided and stabilized sludges are better suited for area filling than are unstabilized sludges.

Three sub-methods have been identified under area fill applications. These include (1) area fill mound, (2) area fill layer, and (3) diked containment. Each of these three sub-methods are described subsequently.

Area Fill Mound

In area fill mound applications, it is recommended that the solids content of sludge received at the site be no lower than 20 percent. Sludge is mixed with a soil bulking agent to produce a mixture which is more stable and has greater bearing capacity. As shown below, appropriate bulking ratios may vary between 0.5 and 2 parts soil for each part of sludge. The exact ratio employed will depend on the solids content of the sludge as received and the need for mound stability and bearing capacity (as dictated by the number of lifts and equipment weight).

The sludge/soil mixing process is usually performed at one location and the mixture hauled to the filling area. At the filling area, the sludge/soil mixture is stacked into mounds approximately 6 ft (1.8 m) high. Cover material is then applied atop these mounds in a minimum 1 ft (0.3 m) thick application. This cover thickness is usually increased to 3 ft (0.9 m) if additional mounds are applied atop the first lift. Relevant sludge and site conditions as well as design criteria are presented in the following tabulation.

Sludge and Site Conditions

Sludge solids content	$\geq$20 percent
Sludge characteristics	stabilized
Hydrogeology	shallow groundwater or bedrock possible
Ground slopes	suitable for steep terrain as long as an area is prepared for mounding

Design Criteria

Bulking required	yes
Bulking agent	soil
Bulking ratio	0.5–2 soil:1 sludge
Cover soil required	yes
Cover soil thickness	3 ft (0.9 m) of interim 1 ft (0.3 m) of final
Imported soil required	yes
Sludge application	3,000–14,000 yd^3/acre (5,700–34,600 m^3/ha)
Equipment	track loader, backhoe with loader, track dozer

Because equipment may pass atop the sludge in performing mixing, mounding, and covering operations, lightweight equipment with swamp pad tracks is generally recommended for area fill mound operations. However, heavier wheel equipment may be more appropriate in transporting bulking material to and from soil stockpiles.

An advantage of the area fill mound operation is its good land utilization. Sludge application rates are relatively high at 3,000 to 14,000 yd^3/acre (5,700 to 26,400 m^3/ha). A disadvantage is the constant need to push and stack slumping mounds. For this reason, area fill mounds often have higher manpower and equipment requirements. Some slumping is inevitable and occurs particularly in high rainfall areas due to moisture additions to the sludge. Slumping can sometimes be minimized by providing earthen containment of mounds where possible. For example, area fill mound operations are usually conducted on level ground to prevent mounds from flowing downhill. However, if a steeply sloping site is selected, a level mounding area could be prepared into the slope and a sidewall created for containment of mounds on one side.

Area Fill Layer

In area fill layer applications, sludge received at the site may be as low as 15 percent solids. Sludge is mixed with a soil bulking agent to produce a mixture which is more stable and has greater bearing capacity. Typical bulking ratios range from 0.25 to 1 part soil for each part sludge. As for area fill mounds, the ratio will depend on the solids content of the sludge as received and the need for layer stability and bearing capacity (as dictated by the number of layers and the equipment weight).

This mixing process may occur either at a separate sludge dumping and mixing area or in the filling area. After mixing the sludge with soil, the mixture is spread evenly in layers from 0.5 to 3 ft (0.15 to 0.9 m) thick. This layering usually continues for a number of applications. Interim cover between consecutive layers may be applied in 0.5 to 1 ft (0.15 to 0.3 m) thick applications. Final cover should be at least 1 ft (0.3 m) thick. Relevant sludge and site conditions as well as design criteria are presented in the following tabulation.

Sludge and Site Conditions

Sludge solids content	≥15 percent
Sludge characteristics	stabilized
Hydrogeology	shallow groundwater or bedrock possible
Ground slopes	suitable for medium slopes but level ground preferred

Design Criteria

Bulking required	yes
Bulking agent	soil
Bulking ratio	0.25–1 soil:1 sludge
Cover soil required	yes
Cover soil thickness	0.5–1 ft (0.15–0.3 m) of interim 1 ft (0.3 m) of final
Imported soil required	yes
Sludge application	2,000–9,000 yd^3/acre (3,800–17,000 m^3/ha)
Equipment	track dozer, grader, track loader

As for mounding operations, equipment will also pass atop sludge in performing mixing, layering, and covering functions. Accordingly, lightweight equipment with swamp pad tracks is generally recommended for area fill layer operations. However, heavier wheel equipment may be appropriate for hauling soil. Slopes in layering areas should be relatively flat to prevent the sludge from flowing downhill. However, if the sludge solids content is high and/or sufficient bulking soil is used, this effect can be prevented and layering performed on mildly sloping terrain.

An advantage of an area fill layer operation is that completed fill areas are relatively stable. As a result, the maintenance required is not as extensive as for area fill mounds. Accordingly, manpower and equipment requirements are less. A disadvantage is poor land utilization with application rates from 2,000 to 9,000 yd^3/acre (3,780 to 17,000 m^3/ha).

Diked Containment

In diked containment applications, sludge is placed entirely above the original ground surface. Dikes are constructed on level ground around all four sides of a containment area. Alternatively, the containment area may be placed at the toe of a hill so that the steep slope can be utilized as containment on one or two sides. Dikes would then be constructed around the remaining sides.

Access is provided to the top of the dikes so that haul vehicles can dump sludge directly into the containment. Interim cover may be applied at certain points during the filling, and final cover should be applied when filling is discontinued. Relevant sludge and site conditions as well as design criteria are presented in the following tabulation.

Sludge and Site Conditions

Sludge solids content	20–28 percent for land-based equipment ≥28 percent for sludge-based equipment
Sludge characteristics	unstabilized or stabilized
Hydrogeology	shallow groundwater or bedrock possible
Ground slopes	suitable for steep terrain as long as a level area is prepared inside dikes

	Design Criteria
Bulking required	no, but sometimes used
Bulking agent	soil
Bulking ratio	0.25–1 soil:1 sludge
Cover soil required	yes
Cover soil thickness	1–2 ft (0.3–0.6 m) of interim with land-based equipment 2–3 ft (0.6–0.9 m) of interim with sludge-based equipment 3–4 ft (0.9–1.2 m) of final with land-based equipment 4–5 ft (1.2–1.5 m) of final with sludge-based equipment
Imported soil required	yes
Sludge application	4,800–15,000 yd^3/acre (9,100–28,400 m^3/ha)
Equipment	dragline, track dozer, scraper

As shown, the solids content of sludge received at diked containments should be a minimum of 20 percent. For sludges with solids contents between 20 and 28 percent, cover material should be applied by equipment based on solid ground atop the dikes. For this situation, a dragline is the best equipment for cover application due to its long reach. Thicknesses should be 1 to 2 ft (0.3 to 0.6 m) for interim cover and 3 to 4 ft (0.9 to 1.2 m) for final cover.

For sludges with solids contents of 28 percent and above, cover material should be applied by equipment which pushes and spreads cover soil into place as it proceeds out over the sludge. For this situation, a track dozer is the best equipment for cover application. Thicknesses should be 2 to 3 ft (0.6 to 0.9 m) for interim cover and 4 to 5 ft (1.2 to 1.5 m) for final cover.

Usually diked containment operations are conducted without the addition of soil bulking agents. The above numbers reflect usual conditions. Occasionally, however, soil bulking is added. Under these circumstances, soil may be added to increase the solids content and allow the operations described above.

An advantage of this method is that individual diked containments are relatively large with typical dimensions of 50 to 100 ft (15 to 30 m) wide, 100 to 200 ft (30 to 60 ft) long, and 10 to 30 ft (3 to 9 m) deep. Accordingly, efficient land use is realized with sludge loading rates varying between 4,800 and 15,000 yd^3/acre (9,100 to 28,400 m^3/ha). A disadvantage of diked containment is that the depth of the fill in conjunction with the weight of interim and final cover places a significant surcharge on the sludge. As a result, much of the sludge moisture is squeezed into surrounding dikes and into the floor of the containment. Accordingly, liners and other leachate controls may be especially appropriate with diked containments to collect leachate emissions.

Codisposal

A codisposal operation is defined as the receipt of sludge at a refuse landfill. Two sub-methods have been identified under codisposal operations. These include (1) sludge/refuse mixture and (2) sludge/soil mixture.

Sludge/Refuse Mixture

In a sludge/refuse mixture operation, sludge is deposited at the working face of the landfill and applied atop refuse. The sludge and refuse are then mixed as thoroughly as possible. This mixture is then spread, compacted, and covered in the usual manner at a refuse landfill. Relevant sludge and site conditions as well as design criteria are presented in the following tabulation.

	Sludge and Site Conditions
Sludge solids content	$\geq$3 percent
Sludge characteristics	unstabilized or stabilized
Hydrogeology	deep or shallow groundwater or bedrock
Ground slopes	$<$30 percent
	Design Criteria
Bulking required	yes
Bulking agent	refuse
Bulking ratio	4–7 tons refuse:1 wet ton sludge
Cover soil required	yes
Cover soil thickness	0.5–1 ft (0.15–0.3 m) of interim 2 ft (0.6 m) of final
Imported soil required	no
Sludge application	500–4,200 yd^3/acre (900-7,900 m^3/ha)
Equipment	track dozer, track loader

As shown, sludge with solids contents as low as 3 percent may be received in such operations. Usually, such sludge is spray applied from a tank truck to a layer of refuse at the working face. The bulking ratio for a 3 percent solids sludge should be at least 7 tons of refuse to 1 wet ton of sludge (7 Mg of refuse to 1 wet Mg of sludge). Usually, only sludges with solids contents of 20 percent or more are mixed with refuse in such operations. Fewer operational and environmental problems may be expected than when a 3 percent solids sludge is received. Also, less bulking agent is required and ratios as low as 4 tons of refuse to 1 wet ton of sludge (4 Mg of refuse to 1 Mg of sludge) are successfully practiced.

Also as shown, sludge application rates for sludge/refuse mixtures compare favorably with other methods, despite the fact that sludge is not the only waste being disposed on the land. Application rates generally range from 500 to 4,200 yd^3 of sludge per acre (900 to 7,900 m^3 of sludge per ha).

Sludge/Soil Mixture

In a sludge/soil mixture operation, sludge is mixed with soil and applied as interim or final cover over completed areas of the refuse landfill. This is not strictly a sludge landfilling method since the sludge is not buried. However, it is a viable option for disposal of sludge at refuse landfills which has been performed and should be used in many cases. Relevant sludge and site conditions as well as design criteria are presented in the following tabulation.

	Sludge and Site Conditions
Sludge solids content	$\geq$20 percent
Sludge characteristics	stabilized
Hydrogeology	deep or shallow groundwater or bedrock
Ground slopes	$<$5 percent

	Design Criteria
Bulking required	yes
Bulking agent	soil
Bulking ratio	1 soil:1 sludge
Cover soil required	no
Imported soil required	no
Sludge application	1,600 yd^3/acre (3,000 m^3/ha)
Equipment	tractor with disc

One advantage of employing the sludge/soil mixture operation is that it removes sludge from the working face of the landfill where it may cause operational problems. Other advantages are that the mixture can be used to promote vegetation over completed fill areas; a savings in fertilizer can be realized; and siltation and erosion problems can be minimized.

One disadvantage of employing the sludge/soil mixture is that it generally has greater manpower and equipment requirements than would be incurred by landfilling the same sludge quantity at the working face. Another disadvantage is that since the sludge is not completely buried, odors may be more severe than for sludge/refuse mixtures. For this reason, only well stabilized sludges are recommended for use in sludge/soil mixture operations.

Sludge-Only or Codisposal

For a variety of reasons, consideration should be given to using codisposal methods for sludge disposal in lieu of sludge-only methods. The advantages of using an existing refuse landfill instead of a new sludge-only landfill include:

1. Shorter time delay: Processing of permits to dispose sludge at an existing refuse landfill will probably be quicker than processing permits for a new sludge-only site. Also, since most or all of the site preparation required for sludge disposal is in place, delays for construction may not occur.
2. Less environmental impact: The environmental impact (odors, traffic, aesthetics, water) of one codisposal site will probably be less than the combined impacts from two separate sites.
3. Less public opposition: The public is less likely to resist an expansion in the operations of one site than it is to resist the operation of a new site.
4. Less cost: Due to economies of scale, the cost of one codisposal site will probably be less than the combined costs of two separate sites.

Obviously, there are several disadvantages for refuse landfill operators to consider when contemplating the receipt of sludge. These include:

1. Odors may increase somewhat depending upon the degree to which the sludge is stabilized.
2. Leachate may be generated sooner (if not already existing) or leachate quantities may increase (if already existing).
3. Operational problems may develop including equipment slipping or becoming stuck in sludge, or sludge being tracked around the site by equipment and haul vehicles.

Several other items should be considered by a refuse landfill before receiving sludge. These include:

1. Pertinent regulatory authorities should be consulted to ascertain whether sludge receipt is permissible.
2. Leachate collection and treatment systems may have to be enlarged (if existing) or installed (if not existing) to handle any increased leachate quantities.
3. Leachate treatment systems may have to be upgraded to handle any change in leachate quality.
4. A sufficient volume of refuse should be delivered to the site so that sufficient absorption of sludge moisture can occur.
5. Ideally, delivery of sludge and refuse should occur simultaneously. If not, storage capacity must be provided for either sludge or refuse so that the sludge can be mixed with refuse when landfilled.
6. Controlled dumping of refuse should occur to maximize its absorptive capacity with sludge. Such control may not be attainable when the public is allowed access to the working face.

Conclusion

The major sludge landfilling methods have been identified and described. Sludge and site conditions as well as design criteria have been presented for each method.

Tables 10–2 and 10–3 are compilations of the conditions and criteria presented previously for each landfilling method. They are provided to give guidance during the investigation of alternative sites and landfilling methods. It is important to note that there is no one best method for a given sludge or site. Rather, these considerations and criteria merely suggest sites and amenable landfilling methods that can simplify and improve the design and operational procedures required for an environmentally safe and cost-effective sludge landfill.

DESIGN

The sludge landfill design directs and guides the construction and on-going operation of the landfill. A design should ensure (1) compliance with pertinent regulatory requirements, (2) adequate protection of the environment, and (3) cost-efficient utilization of site manpower, equipment, storage volume, and soil. A design package (consisting of all design documents) should be prepared to provide a record of the landfill design. These may consist of drawings, specifications, and reports.

Regulations and Permits

Many regulatory and approving agencies require permits before a sludge landfill can be constructed or operated. The sludge landfill design is generally an integral part of the application for such permits. Accordingly, all pertinent agencies should be contacted early in the design phase to (1) identify regulations impacting on the

Table 10–2.—Sludge and site conditions

Method	Sludge solids content (percent)	Sludge characteristics	Hydrogeology	Ground slope
Narrow trench..............	15–28	Unstabilized or stabilized	Deep groundwater and bedrock	<20 percent
Wide trench................	≥20	Unstabilized or stabilized	Deep groundwater and bedrock	<10 percent
Area fill mound............	≥20	Stabilized	Shallow groundwater or bedrock	Suitable for steep terrain as long as level area is prepared for mounding
Area fill layer..............	≥15	Unstabilized or stabilized	Shallow groundwater or bedrock	Suitable for medium slopes but level ground preferred
Diked containment.........	≥20	Stabilized	Shallow groundwater or bedrock	Suitable for steep terrain as long as a level area is prepared inside dikes
Sludge/refuse mixture.....	≥3	Unstabilized or stabilized	Deep or shallow groundwater or bedrock	<30 percent
Sludge/soil mixture........	≥20	Stabilized	Deep or shallow groundwater or bedrock	<5 percent

prospective sludge landfill, (2) determine the extent, detail, and format of the application, and (3) obtain any permit application forms. Once this information has been collected, the design phase can proceed in a more efficient manner toward the goal of receiving the necessary permits.

Regulations and permits relevant to sludge landfills are found to exist on the Federal, State, and local levels. Federal regulations relevant to sludge landfills are contained largely in the Criteria for the Classification of Solid Waste Disposal Facilities. These Criteria address the following topic areas:

1. Environmentally sensitive areas.
2. Surface water.
3. Groundwater.
4. Air.
5. Application on land used for the production of food chain crops.
6. Disease vectors.
7. Safety.

Environmentally sensitive areas are more specifically identified as (1) wetlands, (2) flood plains, (3) permafrost areas, (4) critical habitats, and (5) recharge zones for sole source aquifers. As stated in the Criteria, disposal facilities should not be located in environmentally sensitive areas when feasible alternatives exist, unless it can be clearly demonstrated that there will be no significant impact on the ecosystem or human health from the operation of a facility in such an area.[1]

Safety concerns are more specifically identified as (1) explosive gases, (2) toxic or asphyxiating gases, (3) fires, (4) bird hazards to aircraft, and (5) access. As stated in the Criteria, disposal facilities should not pose a safety hazard to facility employees, users, or the public with respect to any of the above features. Requirements also exist in each of the remaining topic areas and the Criteria should be consulted for a complete description.

Many of the requirements in the Criteria are already addressed in State regulations. Table 10–4 provides an analysis of the Criteria topic areas included in State regulations.

Several permits relevant to sludge landfills are identified and mandated by these Criteria. Generally these include:

1. NPDES permit: required for location of a sludge landfill in wetlands. It is also required for any point source discharges at sludge landfills.
2. Army Corps of Engineers permit: required for the construction of any levee, dike, or other type of containment structure to be placed in the water at a sludge landfill located in wetlands.
3. Office of Endangered Species permit: may be required from the Fish and Wildlife Service, Department of the Interior for location of a sludge landfill in critical habitats of endangered species.

State and local regulations and permits are highly variable from jurisdiction to jurisdiction. Depending on the jurisdiction, one or more permits may be required for a sludge landfill. Typical permits on the State and local levels include:

1. Solid waste management permit.
2. Special use permit.
3. Zone change certification for a change to a zoning appropriate for a sludge landfill.

Table 10–3.—Design criteria[a]

Method	Sludge solids content (percent)	Trench width (ft)	Bulking required	Bulking agent	Bulking ratio	Cover required	Method of cover application	Cover thickness (ft)		Imported soil required	Sludge application rate (in actual fill areas)	Equipment
								Interim	Final			
Narrow trench	15–20	2–3	No	—	—	Yes	Land-based equipment	—	2–3	No	1,200–5,600	Backhoe with loader, excavator, trenching machine
	20–28	3–10	No	—		Yes	Land-based equipment	—	3–4			
Wide trench	20–28	>10	No	—	—	Yes	Land-based equipment	—	3–4	No	3,200–14,500	Tractor loader, dragline, scraper, track dozer
	≥28	>10	No	—		Yes	Sludge-based equipment	—	4–5			
Area fill mound	≥20	—	Yes	Soil	0.5–2 soil:1 sludge	Yes	Sludge-based equipment	3	1	Yes	3,000–14,000	Track loader, backhoe with loader, track dozer
Area fill layer	≥15	—	Yes	Soil	0.25–1 soil:1 sludge	Yes	Sludge-based equipment	0.5–1	1	Yes	2,000–9,000	Track dozer, grader, track loader
Diked containment	20–28	—	No[b]	Soil	0.25–0.5 soil:1 sludge	Yes	Land-based equipment	1–2	3–4	Yes	4,800–15,000	Dragline, track dozer, scraper
	≥28	—	No[b]	Soil		Yes	Sludge-based equipment	2–3	4–5			
Sludge/refuse mixture	≥3	—	Yes	Refuse	4–7 tons refuse:1 wet ton sludge	Yes	Sludge-based equipment	0.5–1	2	No	500–4,200	Track dozer, track loader
Sludge/soil mixture	≥20	—	Yes	Soil	1 soil:1 sludge	No	—	—	—	No	1,600	Tractor with disc, grader, track dozer, track loader

[a] Volume basis unless otherwise noted.
[b] But sometimes used.

1 ft = 0.305 m
1 $yd^3 = 0.765\ m^3$
1 acre = 0.405 ha

Table 10–4.—Analysis of Federal criteria versus State regulations[2]

	Environmentally sensitive areas								Safety						
State	Wetlands	Flood plains	Permafrost	Critical habitats	Sole-Source aquifers	Surface water	Groundwater	Air	Disease vectors	Explosive gases	Fires	Toxic gases	Bird hazards	Access	Percent of total[a]
Alabama						X	X	X	X		X				50
Alaska			X			X	X	X	X					X	60
Arizona						X	X	X	X		X				50
Arkansas		X				X	X	X	X		X			X	70
California	X	X		X		X	X	X	X	X	X	X	X	X	100
Colorado		X				X		X	X		X			X	60
Connecticut		X				X			X	X	X	X		X	70
Delaware	X					X	X		X	X				X	60
Florida		X			X	X	X	X	X	X	X	X	X	X	100
Georgia	X					X	X	X	X		X			X	70
Hawaii		X				X			X		X				40
Idaho						X	X	X	X		X			X	60
Illinois						X	X	X	X		X			X	60
Indiana					X	X		X	X	X	X	X		X	80
Iowa		X			X	X		X	X		X			X	60
Kansas								X	X		X			X	40
Kentucky		X				X	X	X	X		X			X	70
Louisiana							X		X						20
Maine	X					X			X		X			X	50
Maryland	X	X				X	X	X	X	X	X	X		X	90
Massachusetts	X	X				X		X	X		X			X	60
Michigan					X	X	X	X	X		X			X	70
Minnesota	X	X				X	X	X	X	X	X	X	X	X	100
Mississippi		X						X	X		X			X	50
Missouri		X				X	X	X	X	X	X	X		X	90
Montana		X				X	X	X	X					X	60
Nebraska		X				X	X	X	X		X			X	70
Nevada						X	X	X	X		X			X	60
New Hampshire	X	X				X	X	X	X	X	X	X		X	90
New Jersey	X					X	X	X	X	X	X	X	X		90
New Mexico						X	X		X		X			X	50
New York						X	X	X	X					X	50
North Carolina		X				X	X	X	X		X			X	70
North Dakota						X			X					X	30
Ohio						X	X		X		X			X	50
Oklahoma						X		X	X		X			X	50
Oregon		X				X	X	X	X		X			X	70
Pennsylvania		X				X	X	X	X		X			X	70
Rhode Island						X	X	X	X	X	X	X		X	80
South Carolina						X	X	X	X					X	50
South Dakota		X				X	X	X	X		X			X	70
Tennessee		X				X	X	X	X		X			X	70
Texas		X				X	X	X	X	X	X	X	X	X	100
Utah						X		X	X		X				40
Vermont						X		X	X					X	40
Virginia						X	X	X	X		X				50
Washington	X	X				X	X	X	X	X	X	X		X	90
West Virginia						X	X	X	X						40
Wisconsin	X					X	X	X	X		X			X	90
Wyoming						X	X	X	X		X			X	60
Total	11/50	23/50	1/50	1/50	4/50	47/50	37/50	42/50	50/50	14/50	41/50	13/50	5/50	42/50	
Percent of total	22	45	2	2	8	94	74	84	100	28	82	26	10	84	

[a]Environmentally sensitive areas counted as one criterion for row totals.

4. Sedimentation control permit for surface runoff into water courses.
5. Highway department permit for entrances on public roads and increased traffic volumes.
6. Construction permit for landfill site preparation.
7. Operation permit for on-going landfill operation.
8. Mining permit for excavations.
9. Fugitive dust permit.
10. Business permit for charging fees.
11. Closure permit.

Depending on local procedures, permits may be required from both state and local regulatory agencies. State regulatory agencies which require such submittals may include:

1. Solid waste management agencies.
2. Water quality control agencies.
3. Health departments.

Local regulatory agencies may include:

1. Health departments.
2. Planning and/or zoning commissions.
3. Board of county commissioners.

In many jurisdictions more than one of the State or local agencies has authority over a disposal site. Also, in some jurisdictions, one agency has control over sludge-only landfills while another agency has control over sanitary landfills receiving both refuse and sludge.

The reviewing agency may require the submittal of information on standard forms or in a prescribed format in order to facilitate the review process. In any event, applicants are responsible for the completeness and accuracy of the application package. The completed application package is then reviewed by the regulatory agency. The time of the review period will vary depending upon the regulatory agency, their attention to detail, the number of applications preceding it, etc. From experience, this process has been found to take at least one month and usually 6 to 12 months. After a permit is issued, it can be valid for various durations, depending largely upon the submittal of inspection/performance reports and the outcome of on-site inspections.

Design Methodology and Data Compilation

Adherence to a carefully planned sequence of activities to develop a sludge landfill design minimizes project delays and expenditures. A checklist of design activities is presented in table 10–5. These activities are listed somewhat in their order of performance. However, in many cases separate tasks can and should be performed concurrently or even out of the order shown completely.

As shown in table 10–5, initial tasks consist of compiling existing information and generating new information on sludge and site conditions. Obviously, some of this information would have already been collected in the site selection phase. Generally however, additional and more detailed information will have to be collected in the design phase.

Table 10–5.—Sludge landfill design checklist

Step	Task
1	Determine sludge volumes and characteristics
	a. Existing
	b. Projected
2	Compile existing and generate new site information
	a. Perform boundary and topographic survey
	b. Prepare base map of existing conditions on-site and near-site
	(1) Property boundaries
	(2) Topography and slopes
	(3) Surface water
	(4) Utilities
	(5) Roads
	(6) Structures
	(7) Land use
	c. Compile hydrogeological information and prepare location map
	(1) Soils (depth, texture, structure, bulk density, porosity, permeability, moisture, ease of excavation, stability, pH, and cation exchange capacity)
	(2) Bedrock (depth, type, presence of fractures, location of surface outcrops)
	(3) Groundwater (average depth, seasonal fluctuations, hydraulic gradient and direction of flow, rate of flow, quality, uses)
	d. Compile climatological data
	(1) Precipitation
	(2) Evaporation
	(3) Temperature
	(4) Number of freezing days
	(5) Wind direction
	e. Identify regulations (Federal, State, and local) and design standards
	(1) Requirements for sludge stabilization
	(2) Sludge loading rates
	(3) Frequency of cover
	(4) Distances to residences, roads, and surface water
	(5) Monitoring
	(6) Roads
	(7) Building codes
	(8) Contents of application for permit
3	Design filling area
	a. Select landfilling method based on:
	(1) Sludge characteristics
	(2) Site topography and slopes
	(3) Site soils
	(4) Site bedrock
	(5) Site groundwater
	b. Specify design dimensions
	(1) Trench width
	(2) Trench depth
	(3) Trench length
	(4) Trench spacing
	(5) Sludge fill depth
	(6) Interim cover soil thickness
	(7) Final cover soil thickness
	e. Specify operational features
	(1) Use of bulking agent
	(2) Type of bulking agent
	(3) Bulking ratio
	(4) Use of cover soil
	(5) Method of cover application
	(6) Need for imported soil

Table 10–5.—Sludge landfill design checklist—continued

Step	Task
	(7) Equipment requirements
	(8) Personnel requirements
	d. Compute sludge and soil uses
	(1) Sludge application rate
	(2) Soil requirements
4	Design facilities
	a. Leachate controls
	b. Gas controls
	c. Surface water controls
	d. Access roads
	e. Special working areas
	f. Structures
	g. Utilities
	h. Fencing
	i. Lighting
	j. Washracks
	k. Monitoring wells
	l. Landscaping
5	Prepare design package
	a. Develop preliminary location plan of fill areas
	b. Develop landfill contour plans
	(1) Excavation plans
	(2) Completed fill plans
	c. Compute sludge storage volume, soil requirement volumes, and site life
	d. Develop final location plan showing
	(1) Normal fill areas
	(2) Special working areas
	(3) Leachate controls
	(4) Gas controls
	(5) Surface water controls
	(6) Access roads
	(7) Structures
	(8) Utilities
	(9) Fencing
	(10) Lighting
	(11) Washracks
	(12) Monitoring wells
	(13) Landscaping
	e. Prepare elevation plans with cross-sections of:
	(1) Excavated fill
	(2) Completed fill
	(3) Phased development of fill at interim points
	f. Prepare construction details
	(1) Leachate controls
	(2) Gas controls
	(3) Surface water controls
	(4) Access roads
	(5) Structures
	(6) Monitoring wells
	g. Prepare cost estimate
	h. Prepare design report
	i. Submit application and obtain required permits
	j. Prepare operator's manual

Information utilized during both the site selection and design phases can be derived either from existing sources or new sources (i.e., field investigation). A listing of possible existing information sources has been included as table 10–6. A listing of possible new information sources has been included in table 10–7.

Before proceeding to the final design it is advisable to recontact regulatory agencies who were contacted during the site selection process and others to try to determine all of their requirements and procedures for permit application submittals. This will also provide an opportunity to discuss design concepts, get questions answered, and determine any special or new requirements. Maintenance of close liaison with state and local regulatory officials throughout the design effort is normally helpful in securing a permit without excessive redesigns.

A complete design package may include plans, specifications, a design report, cost estimate, and operator's manual. Generally, the cost estimate and operator's manual are prepared strictly for in-house uses, while plans, specifications, and design reports are submitted to regulatory agencies in the permit application. The contents of plans and specifications typically include:

1. Base map showing existing site conditions. The map should be of sufficient detail, with contour intervals of no more than 5 ft (1.5 m) and a scale not to exceed 1 in. = 200 ft (1 cm = 24 m).
2. Site preparation plan locating sludge fill and soil stockpile areas as well as site facilities. A small-scale version of a site preparation plan has been included as figure 10–1.
3. Development plan showing initial excavated and final completed contours in sludge filling areas.
4. Elevations showing cross-sections to illustrate phased development of sludge landfill at several interim points.
5. Construction details illustrating detailed construction of site facilities.
6. Completed site plan including final site landscaping, appurtenances, and other improvements.

The contents of a design report typically include:

1. Site description including existing site size, topography and slopes, surface water, utilities, roads, structures, land use, soils, groundwater, bedrock, and climatology.
2. Design criteria including sludge types and volumes and fill area design dimensions.
3. Operational procedures including site preparation, sludge unloading, sludge handling, and sludge covering as well as equipment and personnel requirements.
4. Environmental safeguards including control of leachate, surface water, gas, odor, flies, etc.

Selection of Landfilling Method

As shown in table 10–2, the most significant features affecting method selection are:

1. Sludge percent solids.
2. Sludge characteristics (stabilized or unstabilized).

Table 10–6.—Sources of existing information

General information	Specific information	Source
Base map	General	County road department City, county, or regional planning department U.S. Geological Survey (USGS) office or outlets for USGS map sales (such as engineering supply stores and sporting goods stores) U.S. Department of Agriculture (USDA), Agricultural Stabilization and Conservation Service (ASCS) Local office of USGS County Department of Agriculture, Soil Conservation Service (SCS) Surveyors and aerial photographers in the area
	Topography and sludge	USGS topographic maps USDA, ARS, SCS aerial photos
	Land use	City, county, or regional planning agency
	Vegetation	County agricultural department Agriculture department at local university
Soils............	General	USDA, Soil Conservation Service (SCS) District Managers, Local Extension Service USGS reports Geology or Agriculture Department of local university
Bedrock........	General	USGS reports State Geological Survey reports Professional geologists in the area Geology Department of local university
Groundwater ..	General	Water Supply Department USGS water supply papers State or regional water quality agencies USDA, SCS State or Federal water resources agencies Local health department
Climatology....	General	National Oceanic and Atmospheric Administration (NOAA) Nearby airports

3. Hydrogeology (deep or shallow groundwater and bedrock)
4. Ground slopes.

One of the purposes of this section is to give specific design information on each landfilling method. It is assumed that a site and landfilling method have already been selected. "Design Example" should be consulted for an illustration of how a landfilling method is selected for a given site.

Sludge-Only Trench Designs

In a sludge-only trench operation, sludge is placed entirely below the original ground surface. Sludge is usually dumped directly into trenches from haul vehicles. On-site equipment is used only to excavate trenches and apply cover; equipment does not usually come into contact with the sludge.

Sludge-only trenches have been further classified into narrow trenches and wide trenches. If one of these landfilling methods has been selected, design of the filling area consists primarily of determining the following parameters:

1. Trench depth.
2. Trench width.
3. Trench length.
4. Trench orientation.
5. Sludge fill depth.
6. Cover thickness.

A methodology for determining these parameters is included in table 10–8.

Trench spacing is perhaps the most important and yet most difficult design parameter to determine. Trench spacing is defined as the width of solid undisturbed ground which is maintained between adjacent trenches. Generally, trench spacing should be as small as possible to optimize land utilization rates. However, the trench spacing must be sufficient to resist sidewall cave-in. Failure of the trench sidewalls is a safety hazard and reduces the volume of the trench available for disposal. Factors to consider in determining trench spacing include: (1) the weight of the excavating machinery, (2) the bearing capacity of the soil (which is a factor of soil cohesion, density, and compaction), (3) saturation level of the soil (which may be significantly influenced by the

Table 10–7.—Field investigations for new information

General information	Specific information	Method and equipment
Base map	Property boundaries	Field survey via transit
	Topography and slopes	Field survey via alidade
	Surface water	Field survey via alidade
	Utilities	Field survey via alidade
	Roads	Field survey via alidade
	Structures	Field survey via alidade
	Land use	Field survey via alidade
	Vegetation	Field survey via alidade
Soils..............	Depth	Soil boring and compilation of boring log
	Texture	Soil sampling and testing via sedimentation methods (e.g., sieves)
	Structure	Soil sampling and inspection
	Bulk density	Soil sampling and testing via gravimetric, gamma ray detection
	Porosity	Calculation using volume of voids and total volume
	Permeability	Soil sampling and testing via piezometers
	Moisture	Soil sampling and testing via oven drying
	Ease of excavation	Test excavation with heavy equipment
	Stability	Test excavation of trench and loading of sidewall
	pH	Soil sampling and testing via pH meter
	Cation exchange capacity	Soil sampling and testing
Bedrock..........	Depth	Boring and compilation of boring log
	Type	Sampling and inspection
	Fractures	Field survey via alidade or Brunton
	Surface outcrops	Field survey via alidade or Brunton
Groundwater	Depth	Well installation and initial readings
	Seasonal fluctuations	Well installation and mean-rand readings
	Hydraulic gradient	Multiple well installation and comparison of readings
	Rate of flow	Calculation based on permeability and hydraulic gradient
	Quality	Groundwater sampling and testing
	Uses	Field survey via inspection

moisture content of the sludge deposited), (4) the depth of the trench, and (5) soil stockpiling and cover placement procedure.

A test which is used primarily to determine the adequacy of soils in highway construction provides general guidance in determining trench configurations (spacing and depth). This test determines the stability of a soil by means of the Hveem stabilometer, which measures the transmitted horizontal pressure due to a vertical load. The stability, expressed as the resistance value (R), represents the shear resistance to plastic deformation of a saturated soil at a given density.[3] This test is described under AASHO T175 (American Association of State Highway Officials).

A general rule of thumb to follow in establishing trench spacing is that for every 1 ft (0.3 m) of trench depth, there should be 1 to 1.5 ft (0.3 to 0.5 m) of space between trenches. If large inter-trench spaces are not practical, the problem of sidewall instability may be relieved by utilizing one of the four trench sidewall variations shown in figure 10–2. In any event, test cell trenches should be used to determine the operational feasibility of any trench design. Such tests should be performed by excavating adjacent trenches to the specified depth, width, and spacing. A haul vehicle fully loaded with sludge should then back up to the trench to determine if the sidewall stability is sufficient.

Using the considerations included in table 10–8, the design parameter can be determined for a variety of sludge and site conditions. These considerations have been employed to develop some alternative design scenarios for trenches shown in table 10–9. In some cases, sludge and site conditions may indicate that it is wholly appropriate to utilize all of the design parameters shown in one of these trench scenarios for application to a real world situation. However, because of the great variety of sludge and site conditions and their combinations, some adaptation of one of these scenarios will be necessary in most cases. In any event, design parameters should not be merely extracted from these tables; parameters should always be well-considered and tested before full-scale application.

Narrow Trench

Narrow trenches have widths less than 10 ft (3.0 m) and usually receive low solids sludge with solids contents as low as 15 percent. Excavation and cover appli-

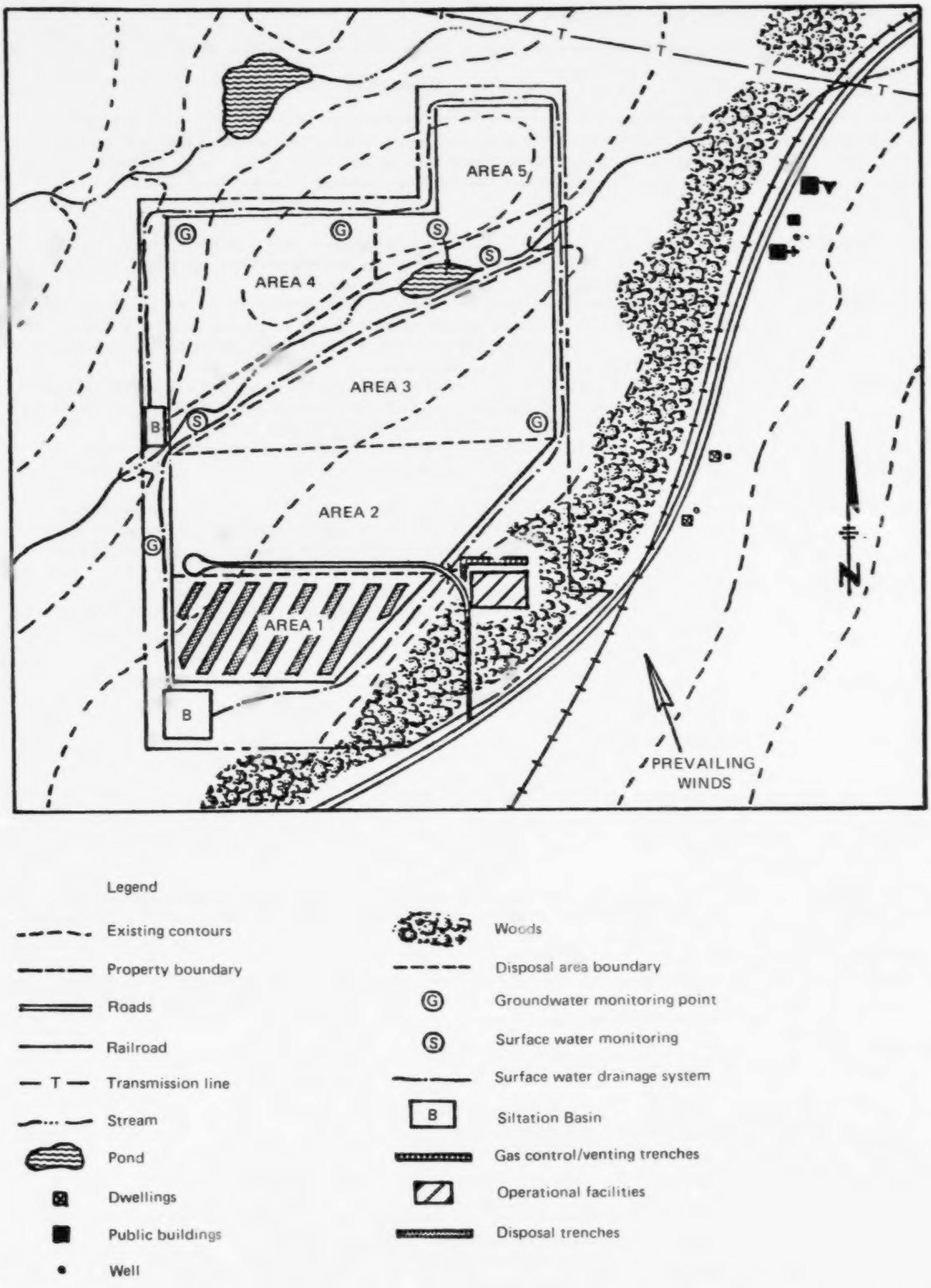
AREA 5
AREA 4
AREA 3
AREA 2
AREA 1
B
B
PREVAILING WINDS
N
Legend
Existing contours
Property boundary
Roads
Railroad
Transmission line
Stream
Pond
Dwellings
Public buildings
Well
Woods
Disposal area boundary
Groundwater monitoring point
Surface water monitoring
Surface water drainage system
Siltation Basin
Gas control/venting trenches
Operational facilities
Disposal trenches

Figure 10–1.—Typical development map.

Table 10-8.—Design considerations for sludge-only trenches

<table>
<tr><th>Design parameter</th><th>Determining factor</th><th>Consideration</th></tr>
<tr><td>Excavation depth</td><td>Depth to groundwater
Depth to bedrock
Soil permeability
Cation exchange capacity of soil</td><td>Sufficient thickness of soil must be maintained between trench bottom and groundwater or bedrock. Required minimum separation varies from 2 to 5 ft. Larger separations-may be required for higher than normal soil permeabilities or sludge loading rates</td></tr>
<tr><td></td><td>Equipment limitations</td><td>Normal excavating equipment can excavate efficiently to depths of 10 ft. Depths from 10 to 20 ft are less efficient operations for normal equipment; larger equipment may be required. Depths over 20 ft are not usually possible.</td></tr>
<tr><td></td><td>Sidewall stability</td><td>Sidewall stability determines maximum depth of trench. If haul vehicles are to dump sludge into trench from above, straight sidewall should be employed. Tests should be performed at site with a loaded haul vehicle to ensure that sidewall height as designed will not collapse under operating conditions.</td></tr>
<tr><td>Spacing</td><td>Sidewall stability</td><td>Trench spacing is determined by sidewall stability. Greater trench spacing will be required when additional sidewall stability is required. As a general rule, 1.0 to 1.5 ft of spacing should be allowed between trenches for every 1 ft of trench depth.</td></tr>
<tr><td></td><td>Soil stockpiles
Vehicle access</td><td>Sufficient space should be maintained between trenches for placement of trench soil stockpiled for cover as well as to allow access and free movement by haul vehicles and operating equipment.</td></tr>
<tr><td>Width</td><td>Sludge solids content</td><td>Widths of 2 to 3 ft for typical sludge with solids content from 15 to 20 percent. Widths of more than 3 ft for typical sludge with solids content more than 20 percent. Certain sludge (e.g., polymer treated) may require higher solids contents before these widths can apply.</td></tr>
<tr><td></td><td>Equipment limitations</td><td>Widths up to 10 ft for typical equipment (such as front end loader) based on solid ground alongside trench. Widths up to 40 ft for some equipment (such as a dragline) based on solid ground. Unlimited widths for cover applied by equipment (such as bulldozers) which proceed out over sludge.</td></tr>
<tr><td></td><td>Equipment efficiencies</td><td><table>
<tr><th><i>Equipment</i></th><th><i>Typical widths (ft)</i></th></tr>
<tr><td>Trenching machine</td><td>2</td></tr>
<tr><td>Backhoe</td><td>2–6</td></tr>
<tr><td>Excavator</td><td>4–22</td></tr>
<tr><td>Track dozer</td><td>≥10</td></tr>
<tr><td>Track loader</td><td>≥10</td></tr>
<tr><td>Dragline</td><td>≥40</td></tr>
<tr><td>Scraper</td><td>≥20</td></tr>
</table></td></tr>
<tr><td>Length</td><td>Sludge solids content
Ground slopes</td><td>If sludge solids are low and/or trench bottoms not level, trench should be discontinued or dikes placed inside trench to contain sludge in one area and prevent it from flowing over large area.</td></tr>
<tr><td>Orientation</td><td>Land availability
Ground slopes</td><td>Trenches should be parallel to optimize land utilization.
For low solids sludge, axis of each trench should be parallel to topographic contours to maintain constant bottom elevation with each trench and prevent sludge from flowing. With higher solids sludge, this requirement is not necessary.</td></tr>
<tr><td>Sludge fill depth</td><td>Trench width</td><td><table>
<tr><th><i>Trench width (ft)</i></th><th><i>Cover application method</i></th><th><i>Minimum distance from top (ft)</i></th></tr>
<tr><td>2–3</td><td>Land-based equipment</td><td>1–2</td></tr>
<tr><td>≥ 3</td><td>Land-based equipment</td><td>3</td></tr>
<tr><td>≥10</td><td>Sludge-based equipment</td><td>4</td></tr>
</table></td></tr>
<tr><td>Cover thickness</td><td>Trench width</td><td><table>
<tr><th><i>Trench width (ft)</i></th><th><i>Cover application method</i></th><th><i>Cover thickness (ft)</i></th></tr>
<tr><td>2–3</td><td>Land-based equipment</td><td>2–3</td></tr>
<tr><td>≥ 3</td><td>Land-based equipment</td><td>3–4</td></tr>
<tr><td>≥10</td><td>Sludge-based equipment</td><td>4–5</td></tr>
</table></td></tr>
</table>

1 ft = 0.305 m.

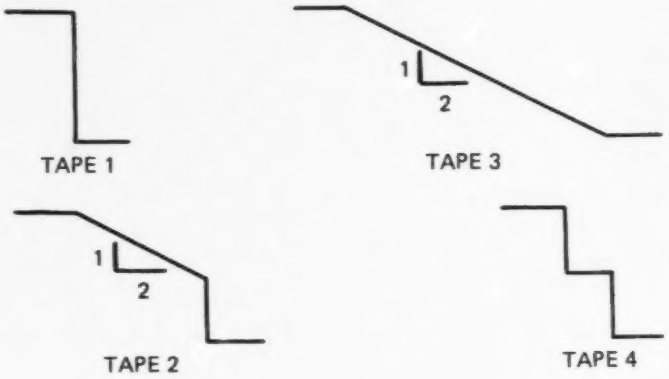

Figure 10–2.—Trench sidewall variations.

cation in narrow trench operations is via equipment based on solid ground alongside the trench. Illustrations of typical narrow trench operations are included as figures 10–3 and 10–4.

The method of sludge placement in a narrow trench is dependent upon the type of haul vehicle and upon trench sidewall stability. Usually trench sidewalls are sufficiently stable and sludge may be dumped from the haul vehicle directly into trenches. However, if sidewalls are not sufficiently stable, the sludge may be delivered to the trench in a chute-extension similar to that found on concrete trucks or pumped in via portable pumps. In some cases (particularly in wet weather) it may be necessary to dump the sludge on solid ground near the trench and have on-site equipment push the sludge into the trench.

Wide Trench

Wide trenches have widths greater than 10 ft (3.0 m) and usually receive higher solids sludge with solids contents of 20 percent and more. Excavation of wide trenches is usually via equipment which enters the trench itself. Cover application may be by equipment based on solid ground alongside the trench, but is usually accomplished by equipment that proceeds out over the sludge spreading a layer of cover soil. Illustrations of typical wide trench operations are included as figures 10–5 and 10–6.

The method of sludge placement in wide trenches may be either (1) from haul vehicles directly entering the trench and dumping sludge in 3 to 4 ft (0.9 to 1.2 m) high piles or (2) from haul vehicles parked at the top of trench sidewalls and dumping sludge into the trench. For the first of these two cases sludge should have a solids content of 32 percent or more to ensure that the sludge will not slump and can be maintained in piles. For the second of these cases, sludge should have a solids content less than 32 percent to ensure that it will flow evenly throughout the trench and not accumulate at the dumping location. Of course, when sludge is free-flowing, some means will be needed to confine the sludge to specific areas in a continuous trench. Dikes are often used for this purpose as illustrated in figure 10–7.

Sludge-Only Area Fill Designs

In a sludge-only area fill operation, sludge is usually placed entirely above the original ground surface. The sludge as received is usually mixed with soil to increase its effective solids content and stability. Several consecutive lifts of this sludge/soil mixture are usually then applied to the filling area. Soil may be applied for interim cover in addition to its usual application for final cover. On-site equipment usually does come into contact with the sludge while performing functions of mixing the sludge with soil; transporting this mixture to the fill area; mounding or layering this mixture; and spreading cover over the mixture.

Sludge-only area fills have been further classified into area fill mounds, area fill layers, and diked containments. If one of these landfilling methods has been selected, design of the filling area may consist primarily of determining the following parameters:

1. Diked containment width.
2. Diked containment sludge fill depth.
3. Height of sludge in each mound or layer.
4. Bulking ratio.
5. Cover thickness.

A methodology for determining these factors is included in table 10–10.

Using the considerations included in table 10–10, the design parameters can be determined for a variety of sludge and site conditions. These considerations have been employed to develop some alternative design scenarios for area fills which were included earlier in table 10–9.

Area Fill Mound

At area fill mound operations, sludge/soil mixtures are stacked into mounds approximately 6 ft (1.8 m) high. Cover soil is applied atop each lift (mounds) in a 1 ft (0.3 m) thickness. The cover thickness is increased to 3 ft (0.9 m) if additional mounds are applied atop the first lift. Illustrations of typical mound operations are included as figures 10–8 and 10–9.

Sludge as received at the landfill is usually mixed with a bulking agent. The bulking agent absorbs excess moisture from the sludge and increases its workability. The amount of soil needed to serve as an additional bulking agent depends upon the solids content of the sludge. Generally the soil requirements shown in table 10–10 may serve as a guideline. Fine sand appears to be the most suitable bulking media because it can most easily absorb the excess moisture from the sludge.

Area Fill Layer

At area fill layer operations, sludge/soil mixtures are spread evenly in layers from 0.5 to 3 ft (0.15 to 0.9 m)

Table 10–9.—Alternative design scenarios

Identification			Site preparation				Sludge bulking			Sludge filling			Sludge covering				Miscellaneous	
Scenario number	Landfilling method	Sludge solids content (percent)	Width (ft)	Depth (ft)	Length (ft)	Spacing (ft)	Bulking performed	Bulking agent	Bulking ratio	Sludge depth per lift (ft)	No of lifts	Sludge application rate (yd^3/acre)	Cover applied	Location of equipment	Cover thickness		Imported soil required	Primary equipment
															Interim (ft)	Final (ft)		
1	Narrow trench	15	2	3	1,000	3	No	—	—	2	1	1,290	Yes	Land-based	—	3	No	Trenching machine
2	Narrow trench	17	2	8	1,000	8	No	—	—	6	1	1,940	Yes	Land-based	—	3	No	Backhoe
3	Narrow trench	25	6	10	100	12	No	—	—	7	1	3,750	Yes	Land-based	—	4	No	Backhoe with loader
4	Narrow trench	28	8	8	100	12	No	—	—	5	1	3,230	Yes	Land-based	—	4	No	Excavator
5	Wide trench	26	40	7	400	20	No	—	—	4	1	4,100	Yes	Land-based	—	4	No	Dragline
6	Wide trench	32	60	8	600	30	No	—	—	4	1	4,100	Yes	Sludge-based	—	5	No	Track dozer
7	Area fill mound	20	—	—	—	—	Yes	Soil	2 soil:1 sludge	6	1	3,230	Yes	Sludge-based	—	2	Yes	Track loader
8	Area fill mound	35	—	—	—	—	Yes	Soil	0.5 soil:1 sludge	6	2	12,910	Yes	Sludge-based	3	1	Yes	Track loader, backhoe with bucket
9	Area fill layer	15	—	—	—	—	Yes	Soil	1 soil:1 sludge	1	3	2,420	Yes	Sludge-based	0.5	1	Yes	Track dozer
10	Area fill layer	30	—	—	—	—	Yes	Soil	.25 soil:1 sludge	3	2	7,740	Yes	Sludge-based	1	1	Yes	Track dozer, grader
11	Diked containment	25	50	30	100	30	Yes	Soil	0.5 soil:1 sludge	6	4	12,410	Yes	Land-based	1	3	No	Dragline
12	Diked containment	32	100	23	200	50	No	—	—	8	2	13,770	Yes	Sludge-based	3	4	No	Track dozer
13	Sludge/refuse mixture	3	—	—	—	—	Yes	Refuse	7 tons refuse:1 wet ton sludge	6	3	2,520	Yes	Sludge-based	0.5	2	No	Track dozer
14	Sludge/refuse mixture	28	—	—	—	—	Yes	Refuse	4 tons refuse:1 wet ton sludge	6	3	4,140	Yes	Sludge-based	0.5	2	No	Track dozer
15	Sludge/soil mixture	20	—	—	—	—	Yes	Soil	1 soil:1 sludge	1.0		1,600	No	—	—	—	No	Tractor with disc

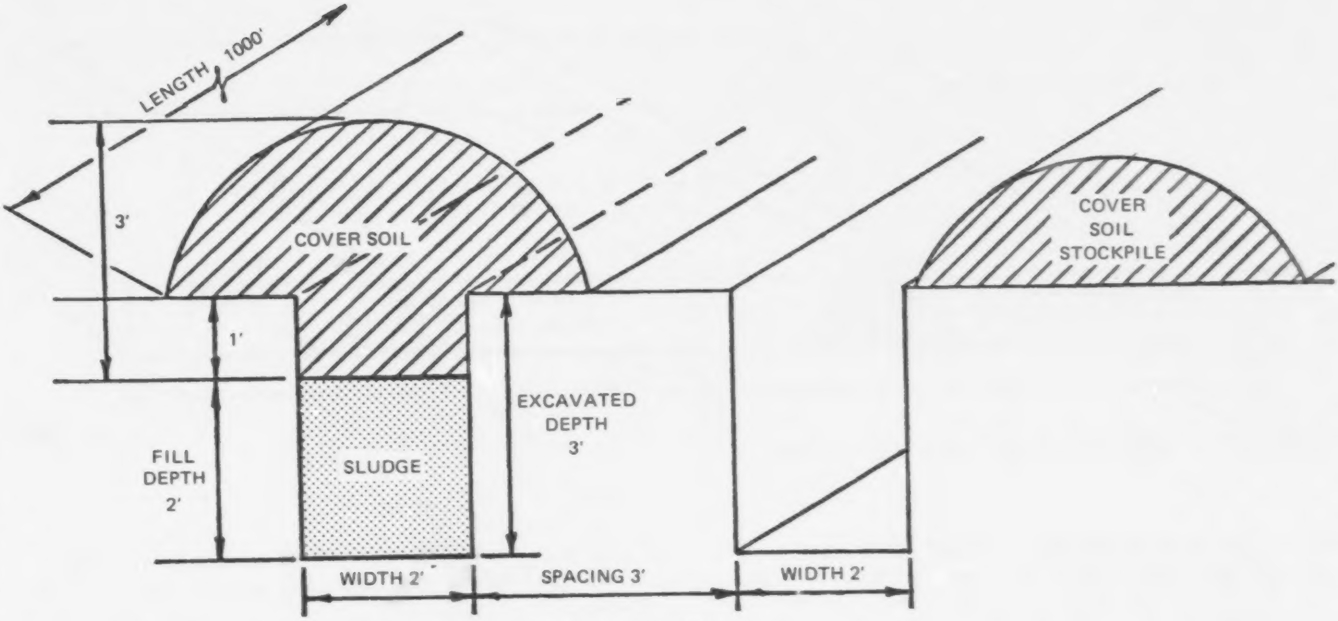
LENGTH 1000'
3'
COVER SOIL
COVER SOIL STOCKPILE
1'
FILL DEPTH 2'
SLUDGE
EXCAVATED DEPTH 3'
WIDTH 2'
SPACING 3'
WIDTH 2'

Figure 10–3.—Cross-section of typical narrow trench operation.

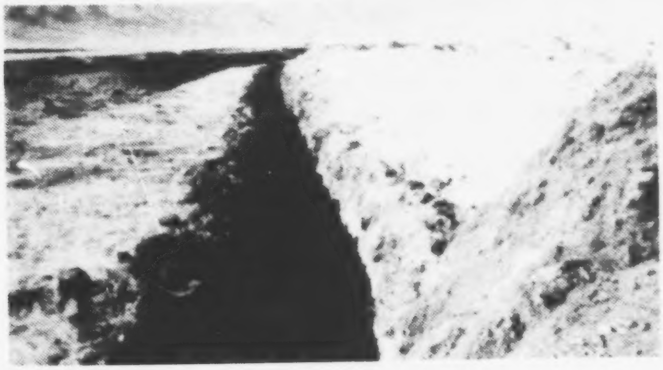

Figure 10–4.—Narrow trench operation.

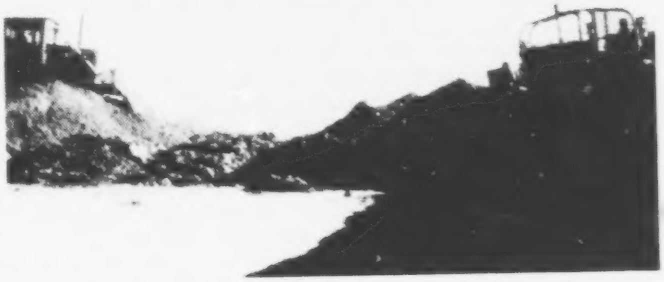

Figure 10–6.—Wide trench operation.

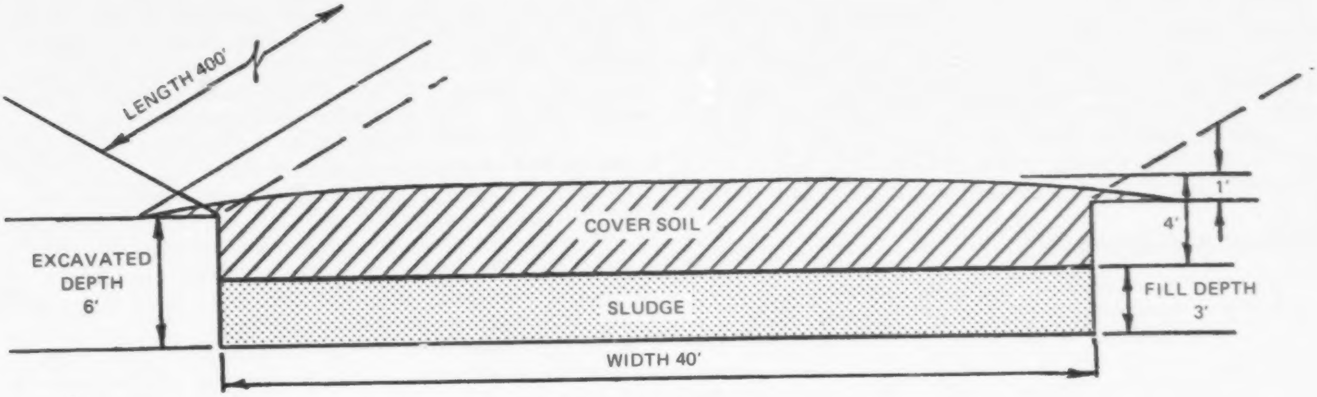
LENGTH 400'
COVER SOIL
1'
4'
EXCAVATED DEPTH 6'
SLUDGE
FILL DEPTH 3'
WIDTH 40'

Figure 10–5.—Cross-section of typical wide trench operation.

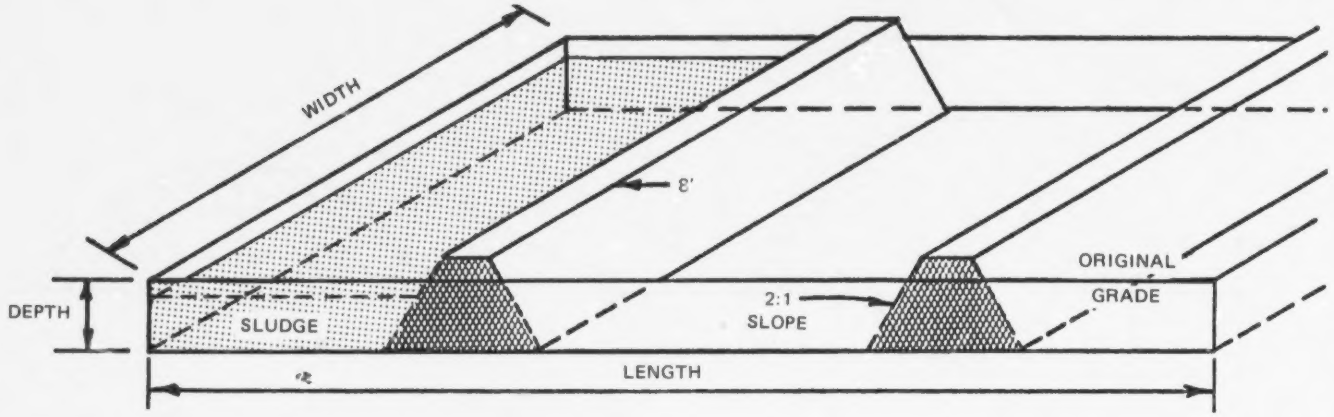

Figure 10–7.—Wide trench with dike cross-section.

thick. This layering usually continues for a number of applications. Interim cover between consecutive layers may be applied in 0.5 to 1 ft (0.5 to 0.3 m) thick applications. Final cover should be at least 1 ft (0.3 m) thick. An illustration of a typical area fill layer operation is included as figure 10–10.

Diked Containment

At diked containment operations, earthen dikes are constructed to form a containment area above the original ground surface. Dikes can be of various heights, but require side slopes of at least 2:1 and possibly 3:1. A 15 ft (4.6 m) wide road, covered with gravel should be constructed atop the dikes.

Sludge may be either (1) mixed with soil bulking for subsequent transport and dumping into the containment area by on-site equipment or (2) dumped directly into the containment area by haul vehicles without bulking soil. Large quantities of imported soil may be required to meet soil requirements for diked construction and bulking since diked containments are often constructed in high groundwater areas.

Sludge is dumped into diked containments in lifts before the application of interim cover. Often this interim cover is a highly permeable drainage blanket which acts as a leachate collection system for sludge moisture released from the sludge lift above. Final cover should be of a less permeable nature and should be graded even with the top of the dikes. An illustration of a typical diked containment operation is included as figure 10–11.

Codisposal Designs

Codisposal is defined as the receipt of sludge at a conventional landfill receiving municipal refuse. Two methods of codisposal have been identified including (1) sludge/refuse mixture and (2) sludge/soil mixture. Design considerations for codisposal landfills have been included in table 10–11. The EPA document, "Sanitary Landfill Design and Operation"[4] should be consulted for further information relating to design and operation of a refuse landfill.

Sludge/Refuse Mixture

In a sludge/refuse mixture operation, sludge is delivered to the working face of the landfill where it is mixed and buried with the refuse. Most of the considerations relative to the receipt of sludge at refuse landfills are operational. Nevertheless, some of the considerations require planning and design solutions.

The first problem encountered at codisposal sites is sludge handling difficulties due to the liquid nature of sludge relative to refuse. Difficulties include (1) the sludge is difficult to confine at the working face since it will readily flow, and (2) equipment slips and sometimes becomes stuck in the sludge while operating at the working face. These difficulties can be minimized if proper planning is employed to control the quantity of sludge received at the refuse landfill. Every effort should be made not to exceed the absorptive capacity of the refuse and obviously, the maximum allowable sludge quantity will vary depending largely on the quantity of refuse received and the solids content of the sludge. Some suggested bulking ratios for sludge/refuse mixtures at various sludge solids contents were included in table 10–11. In any event determinations should be made on a site-by-site basis using test operations.

A second planning and design consideration for sludge/refuse mixture operations concerns leachate control. The impact of sludge receipt on leachate is highly site-specific. Generally, increased leachate quantities should be expected. Leachate control systems may have to be designed or modified accordingly.

A third planning and design consideration is storage for sludge received in off-hours. In many cases sludge is delivered around the clock, whereas refuse delivery is confined to certain hours. Sludge storage facilities may

Table 10–10.—Design considerations for sludge-only area fills

Design parameter	Determining factor	Consideration		
		Method	*Solids content (percent)*	*Bulking ratio*
Bulking ratio.................	Method Sludge solids content	Area fill mound	20–28	2 soil:1 sludge
			28–32	1 soil:1 sludge
			>32	0.5 soil:1 sludge
		Area fill layer	15–20	1 soil:1 sludge
			20–28	0.5 soil:1 sludge
			28–32	0.25 soil:1 sludge
			>32	Not required
		Diked containment	20–28	0.5 soil:1 sludge
			28–32	0.25 soil:1 sludge
			≥32	Not required
		Method	*Solids content (percent)*	*Cover application procedure*
Cover application...........	Method Sludge solids content	Area fill mound	≥20	Sludge-based equipment
		Area fill layer	≥15	Sludge-based equipment
		Diked containment	20–28	Land-based equipment
			≥28	Sludge-based equipment
		Cover application procedure	*Equipment used*	*Width (ft)*
Width of diked containment	Cover application procedure Equipment used	Land-based equipment	Dragline	≤40
		Sludge-based equipment	Track dozer	Not limited
		Method	*Sludge solids (percent)*	*Lift depth (ft)*
Depth of each lift	Method Sludge solids content	Area fill mound	≥20	6
		Area fill layer	15–20	1
			≥20	2–3
		Diked containment	20–28	4–6
			≥28	6–10
		Method	*Cover application procedure*	*Interim cover thickness (ft)*
Interim cover thickness	Method Cover application procedure	Area fill mound	Sludge-based equipment	3
		Area fill layer	Sludge-based equipment	0.5–1
		Diked containment	Land-based equipment	1–2
			Sludge-based equipment	2–3
		Method	*Sludge solids content (percent)*	*Number of lifts*
Number of lifts..............	Method Sludge solids content	Area fill mound	20–28	1 maximum
			≥28	3 maximum
		Area fill layer	≥15	1–3 typical
		Diked containment	≥20	1–3 typical
		Cover application procedure	*Depth of total fill*	
Depth of total fill of diked	Cover application procedure	Land-based equipment	No higher than 3 ft below top of dikes	
		Sludge-based equipment	No higher than 4 ft below top of dikes	
		Method	*Cover application procedure*	*Final cover thickness (ft)*
Final cover thickness	Method Cover application procedure	Area fill mound	Sludge-based equipment	1
		Area fill layer	Sludge-based equipment	1
		Diked containment	Land-based equipment	3–4
			Sludge-based equipment	4–5

1 ft = 0.305 m.

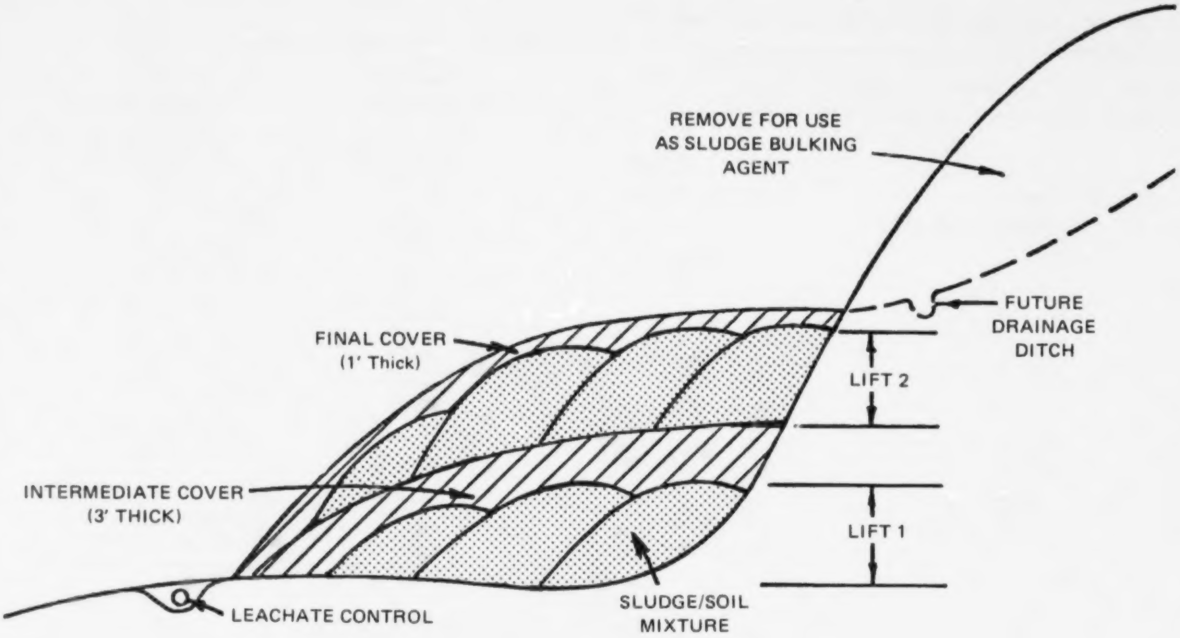
REMOVE FOR USE AS SLUDGE BULKING AGENT
FUTURE DRAINAGE DITCH
FINAL COVER (1' Thick)
LIFT 2
INTERMEDIATE COVER (3' THICK)
LIFT 1
LEACHATE CONTROL
SLUDGE/SOIL MIXTURE

Figure 10–8.—Cross-section of typical area fill mound operation.

Figure 10–9.—Area fill mound operation.

have to be installed to contain sludge overnight until sufficient refuse bulking is delivered.

Sludge/Soil Mixture

In a sludge/soil mixture operation, sludge is mixed with soil and applied as cover over completed refuse fill areas. Most of the considerations associated with these operations are also of an operational nature. However, at the planning and design stage, an area must be reserved for sludge/soil mixing. This area must be sufficiently sized and have sufficient soil available for sludge bulking. Information on a suggested bulking ratio was included in table 10–11. The soils in this area must also be adequate to protect the groundwater.

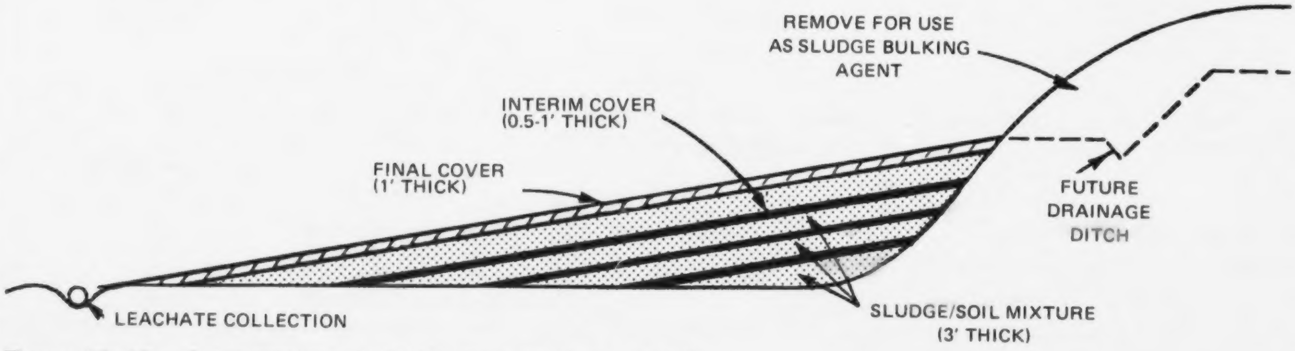
REMOVE FOR USE AS SLUDGE BULKING AGENT
INTERIM COVER (0.5-1' THICK)
FINAL COVER (1' THICK)
FUTURE DRAINAGE DITCH
LEACHATE COLLECTION
SLUDGE/SOIL MIXTURE (3' THICK)

Figure 10–10.—Cross-section of typical area fill layer operation.

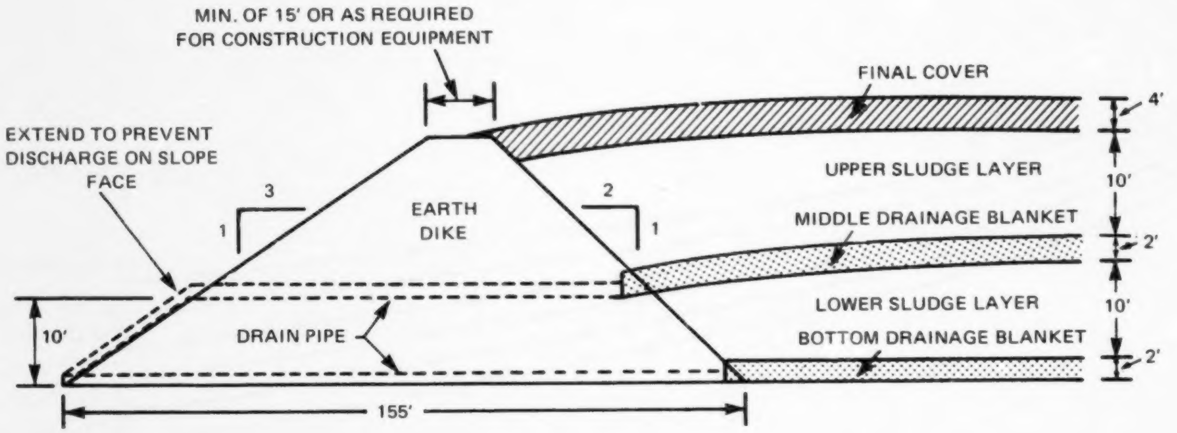
MIN. OF 15' OR AS REQUIRED FOR CONSTRUCTION EQUIPMENT
FINAL COVER
4'
EXTEND TO PREVENT DISCHARGE ON SLOPE FACE
3
1
EARTH DIKE
2
1
UPPER SLUDGE LAYER
10'
MIDDLE DRAINAGE BLANKET
2'
LOWER SLUDGE LAYER
10'
10'
DRAIN PIPE
BOTTOM DRAINAGE BLANKET
2'
155'

Figure 10–11.—Cross-section of typical diked containment operation.

Table 10–11.—Design considerations for codisposal operations

Design parameter	Determining factor	Consideration			
		Method	Bulking agent	Sludge solids content (percent)	Bulking ratio
Bulking ratio	Method	Sludge/refuse mixture	Refuse	3–10	7 tons refuse:1 wet ton sludge
	Bulking agent			10–17	6 tons refuse:1 wet ton sludge
	Sludge solids content			17–20	5 tons refuse:1 wet ton sludge
				≥20	4 tons refuse:1 wet ton sludge
		Sludge/soil mixture	Soil	≥20	1 soil:1 sludge

1 ton = 0.907 Mg.

COSTS

Purpose and Scope

This section presents typical costs for sludge hauling and landfilling. Cost curves are presented in terms of cost per wet ton VS sludge quantity received. Typical costs are presented for (1) sludge hauling, (2) annualized site capital costs, (3) site operating costs, and (4) total site costs (combined annualized capital and operating).

These curves can be useful in the early stages of sludge landfill planning. However, typical costs should be used only in preliminary work. Actual costs vary considerably with specific sludge and site conditions. Therefore, use of these curves for computing specific project costs is not recommended. Site-specific cost investigations should be made in each case.

Hauling Costs

Typical costs for hauling wastewater treatment sludge are presented in figure 10–12. As shown, costs are given in dollars per wet ton as a function of the wet tons of sludge delivered to the site each day. Costs are presented for alternative distances of 5, 10, 20, 30, 40, and 50 mile (8.0, 16.1, 32.2, 48.3, 64.4, and 80.4 km) hauls.

"Principles and Design Criteria for Sewage Sludge Application on Land"[5] and "Transport of Sewage Sludge"[6] were the primary sources of information for data and procedures in developing these hauling costs. Other references[7-10] are available and were also consulted and utilized. Sludge hauling costs were originally prepared for the year 1975 but were updated to reflect 1978 costs.

The hauling costs shown in figure 10–12 reflect not only transportation costs, but also the cost of sludge loading and unloading facilities. For a plant producing

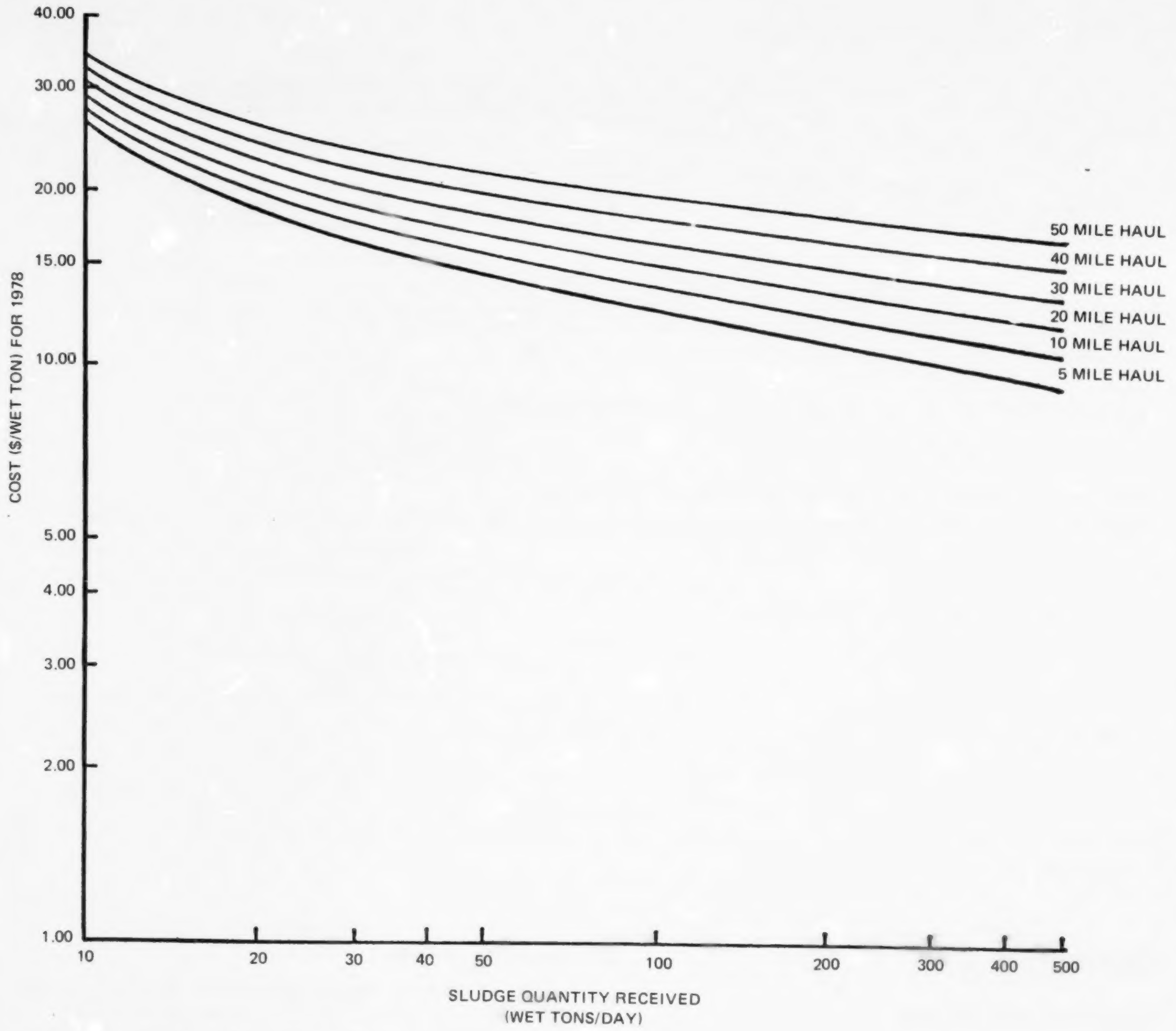

Figure 10–12.—Typical hauling costs.

approximately 10 wet tons (9.1 Mg) per day of a dewatered sludge and a 5-mile (8.0 km) haul, sludge loading and unloading facilities were found to contribute 60 percent of the total hauling costs. For a plant producing approximately 250 wet tons (227 Mg) per day of dewatered sludge and a 40-mile haul, loading and unloading facilities contributed less than 10 percent of the total hauling costs.

Because of the differing bases for cost computations, certain assumptions on sludge volumes and unit costs were utilized to produce the hauling cost curve. These assumptions include:

1. The sludge was dewatered and had a solids content of approximately 20 percent. It was hauled by a 15 yd^3 (11.5 m^3), 3-axle dump truck.
2. Hauling was performed 8 hours per day, 7 days per week.
3. Fuel cost was $0.60 per gallon ($0.16 per liter).
4. Labor (primarily truck driving) cost was $8.00 including fringe benefits.

5. Overhead and administrative costs were 25 percent of the operating cost.
6. Capital costs were annualized. A rate of 7 percent over 6 years was used for the trucks with a salvage value of 15 percent. A rate of 7 percent over 25 years was used for loading and unloading facilities with no salvage value.

If conditions other than the above-stated conditions prevail at a given site, the hauling costs in figure 10-12 should be revised upward or downward appropriately. As an example, if 10 yd^3 (7.6 m^3) 2-axle dump trucks are used, costs should be higher by factors ranging from 1.3 for a plant generating 250 wet tons (227 wet Mg) per day with a 50-mile (80 km) haul to 1.0 for a plant generating 10 wet tons (9.1 wet Mg) per day with a 5-mile (8.0 km) haul. Alternatively, if a 30 yd^3 (23.9 m^3) dump truck is used, costs should be lower by factors ranging from 0.6 to 1.0 for the aforementioned sludge quantities and haul distances.

Site Costs

Typical site costs for landfilling wastewater treatment sludges are presented in figures 10–13, 10–14, and 10–15. As shown, costs are given in dollars per wet ton of sludge received as a function of the wet tons of sludge delivered to the site each day. Costs are presented for each of the alternative landfilling methods. Scenarios using average design dimensions and application rates were devised for the purposes of these cost calculations. These scenarios are summarized in table 10–12. The cost curve for each method was plotted from computations which assumed alternative quantities of 10, 100, and 500 wet tons (9.1, 90.7, and 453 Mg) of sludge for each scenario.

Capital costs are summarized in figure 10–13. Capital cost items included:

1. Land.
2. Site preparation (clearing and grubbing, surface water control ditches and ponds, monitoring wells, soil stockpiles, roads, and facilities).
3. Equipment purchase.
4. Engineering.

Capital costs were then annualized at 7 percent interest over 5 years (the life of the site) and divided by the sludge quantity delivered to the site in one year.

Operating costs are summarized in figure 10–14. Operating cost items included:

1. Labor.
2. Equipment fuel, maintenance, and parts.
3. Utilities.
4. Laboratory analysis of water samples.
5. Supplies and materials.
6. Miscellaneous and other.

Operating costs for one year were then divided by the annual sludge quantity delivered to the site.

The costs shown have been derived from a variety of published information sources[10–12] and case study investigations have been revised upward to reflect 1978 prices. Several assumptions were employed in producing these cost curves. These assumptions include:

1. Life of the landfill site was 5 years.
2. Land cost was $2,500 per acre ($6,177 per ha).
3. Actual fill areas (including inter-trench spaces) consumed 50 percent of the total site area.
4. Engineering was 6 percent of the total capital cost.
5. Operating labor cost $8.00 per hour including fringe overhead, and administration.

It should be noted that the site costs shown for codisposal operations were derived by dividing the additional annualized capital cost and additional operating cost by the sludge quantity received. Actual unit costs for typical refuse landfills not receiving sludge may be expected to be less.

Cost Analysis

As stated previously, these cost curves should not be used for site-specific cost compilations performed during design. However, they can be useful in the preliminary planning stages of a specific sludge landfill. In addition they are useful in developing some general conclusions about sludge landfill costs. For instance, cost ranges included:

1. Hauling costs ranges from $8.80 per wet ton ($9.70 per Mg) (for a 5 mile (8.1 km) haul of 500 wet tons (453 Mg) per day) to $34.00 per wet ton ($37.49 per Mg) (for a 50 mile (80.4 km) haul of 10 wet tons (9.1 Mg) per day).
2. Annualized site capital costs ranged from $2.20 per wet ton ($2.43 per Mg) (for a sludge/refuse codisposal operation receiving 500 wet tons (453 Mg) per day) to $10.10 per wet tons ($11.11 per Mg) (for a diked containment operation receiving 10 wet tons (9.1 Mg) per day).
3. Site operating costs ranged from $1.20 per wet ton ($1.32 per Mg) (for a sludge/refuse codisposal operation receiving 500 wet tons (453 Mg) per day) to $36.10 per wet ton ($39.80 per Mg) (for an area fill mound operation receiving 10 wet tons (9.1 wet Mg) per day).
4. Combined site costs ranged from $3.40 per wet ton ($3.75 per Mg) (for a sludge/refuse codisposal operation receiving 500 wet tons (453 Mg) per day) to $46.20 per wet ton ($50.94 ton Mg) (for an area fill mound operation receiving 10 wet tons (9.1 Mg) per day).

Also, an assessment can be made of the relative costs of alternative landfilling methods. A prioritized list of landfilling methods is based on total site costs (with lowest costs first) is as follows:

1. Codisposal with sludge/refuse mixture.
2. Wide trench.
3. Codisposal with sludge/soil mixture.

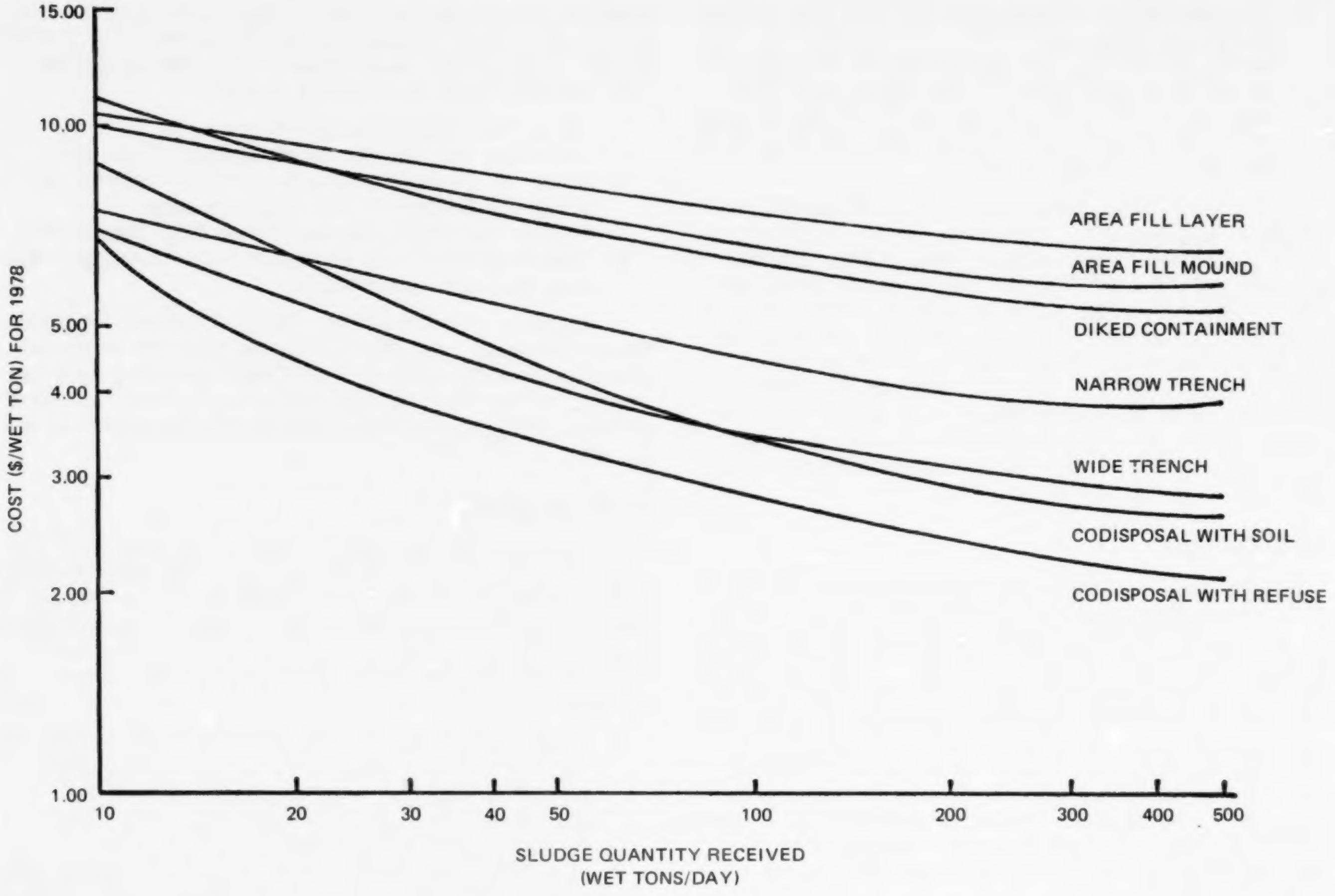

Figure 10–13.—Typical annualized site capital costs.

4. Narrow trench.
5. Diked containment.
6. Area fill layer.
7. Area fill mound.

CASE STUDY

Background and History

The Newport Township landfill, located near Waukegan, Ill., receives sludge generated by four treatment plants that serve a domestic population of 232,000 with an additional industrial inflow equivalent to 28,000 residents. The industrial inflow originates primarily from a naval base, a pharmaceutical company and a variety of metal finishing plants. There are three advanced wastewater plants and one pretreatment wastewater plant within the North Shore Sanitary District. The three advanced treatment plants use activated sludge, followed by biological denitrification and sand filtration; the pretreatment plant uses trickling filters. Figure 10–16 and table 10–13 outline sludge processing at the wastewater treatment plant. After initial processing, sludge from the four plants is taken to a processing plant in Waukegan where it is elutriated and conditioned with lime and ferric chloride. It is then dried to about 22 percent solids by vacuum filtration (figure 10–17) prior to landfilling. The site commenced operations on July 8, 1974.

Site Description

The site has an area of 282.8 acres (114 ha), with 200 acres (81 ha) to be filled. Soils consist of 2 ft (0.6 m) of topsoil, then 20 to 25 ft (6 to 8 m) of silty clays, followed by 6 to 15 ft (2 to 5 m) of tight blue clay. The southwestern part of the site is a flood plain with slopes of less than 1 percent. The flood plain is not being used for filling operations.

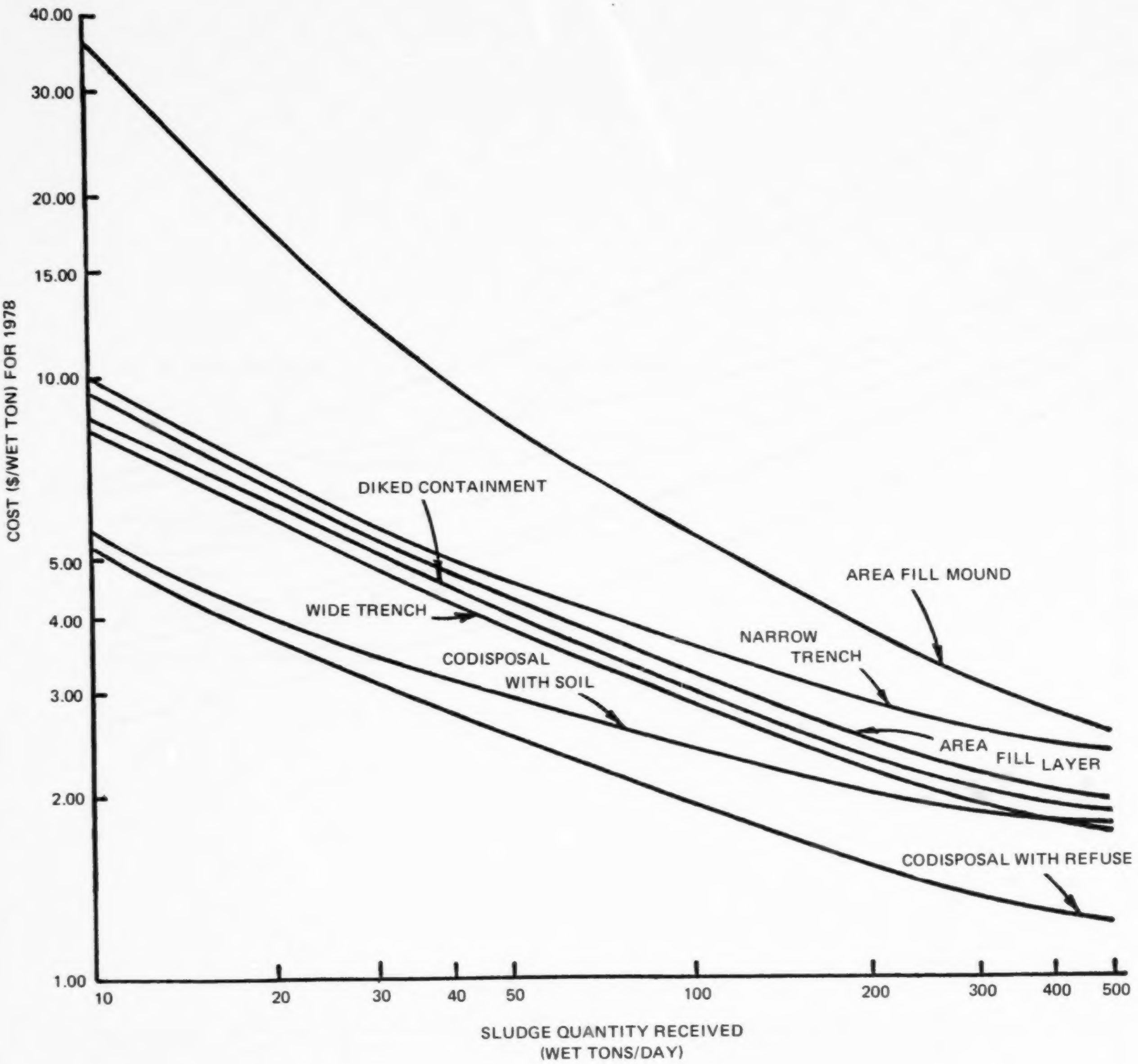

Figure 10–14.—Typical site operating costs.

Topography	slopes average 4 percent; vegetation sparse; flood plain on west end has 1 percent slopes
Soil type	silty clay
Depth to groundwater	31 to 40 ft (10 to 12 m); perched table at 25 ft (8 m)
Groundwater use	aquifer provides potable water
Freezing days	140 days per year
Precipitation	32 in. per year (81 cm/yr)
Evaporation	39 in. per year (99 cm/yr)

Site Selection

The first step in the selection process was to identify the disposal alternatives. The options included:

1. Incineration of dewatered raw and digested sludges.
2. Disposal of digested, dewatered sludge on cropland by discing or plowing into the soil.
3. Disposal of digested liquid sludge on cropland by irrigation.

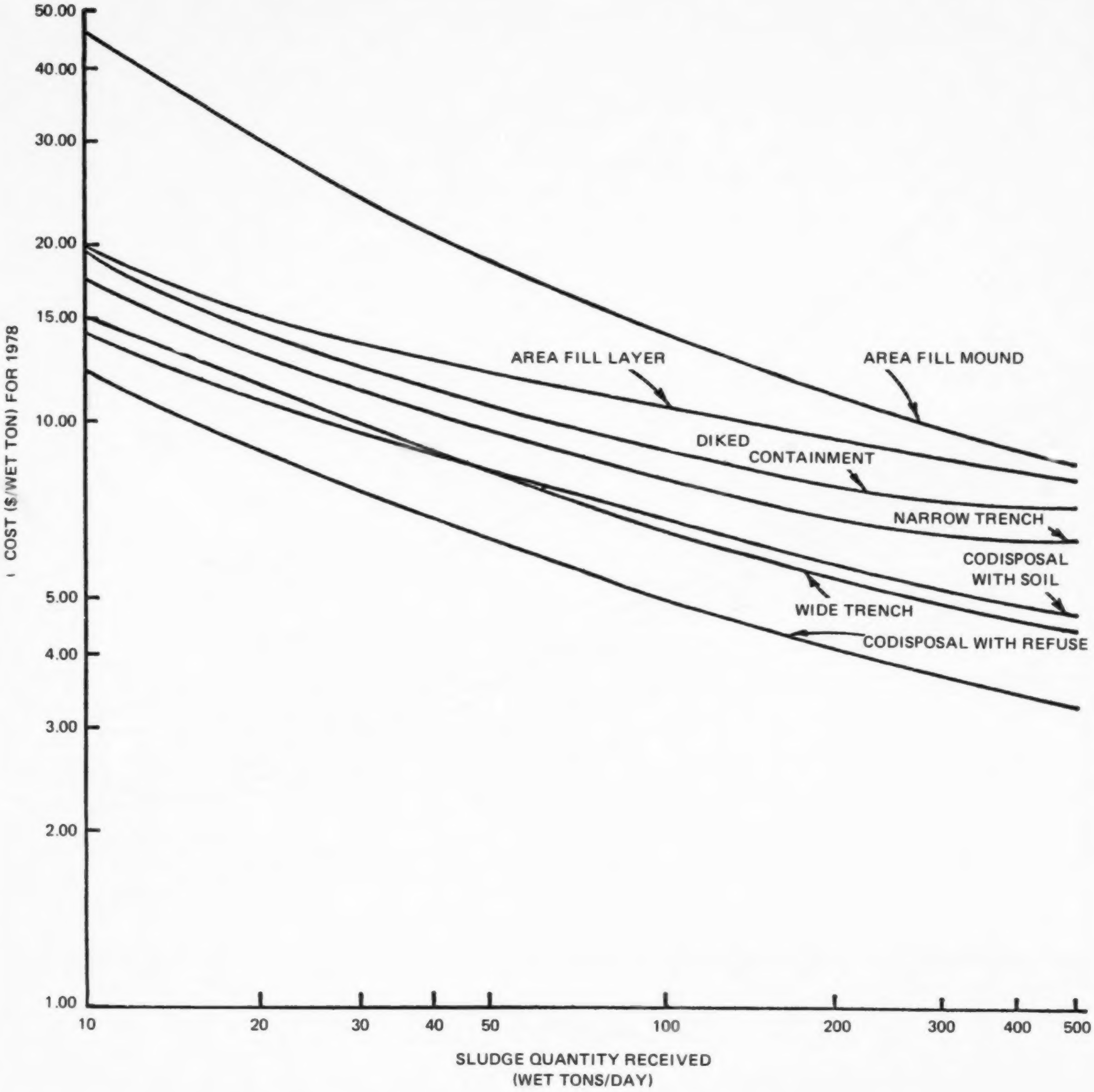

Figure 10–15.—Typical total site costs (combined annualized capital and operating costs).

4. Landfilling of dewatered raw and digested sludges.

Figure 10–18 illustrates the estimated costs of treatment, transportation and disposal for each alternative. On the basis of these cost evaluations and a maximum distance of 25 mi (40 km) to the landfill, it was determined that sludge landfilling would provide the most cost effective alternative for ultimate disposal.

Following selection of the disposal alternative, eight potential sites were chosen and evaluated using available data. Ultimately the Newport Township site was

Table 10–12.—Cost scenarios for alternative landfilling methods

Cost scenario number	Landfilling method	Sludge solids content (percent)	Width (ft)	Depth (ft)	Length (ft)	Spacing (ft)	Bulking per-formed	Bulking agent	Bulking ratio	Sludge depth per lift (ft)	Num-ber of lifts	Sludge applica-tion rate (yd^3/acre)
1........	Narrow trench	22	6	6	100	9	No	—	—	4	1	2,580
2........	Wide trench	32	60	8	600	30	No	—	—	4	1	4,100
3........	Area fill mound	30	—	—	—	—	Yes	Soil	1 soil:1 sludge	6	2	9,680
4........	Area fill layer	30	—	—	—	—	Yes	Soil	0.5 soil:1 sludge	2	2	4,300
5........	Diked containment	25	50	30	100	30	Yes	Soil	0.5 soil:1 sludge	6	4	12,410
6........	Sludge/refuse mixture	20	—	—	—	—	Yes	Refuse	7 tons refuse:1 wet ton sludge	6	3	2,520
7........	Sludge/soil mixture	20	—	—	—	—	Yes	Soil	1 soil:1 sludge	1	1	1,600

Identification			Sludge covering				Miscellaneous	
					Cover thickness			
Cost scenario number	Landfilling method	Sludge solids content (percent)	Cover applied	Location equipment	Interim (ft)	Final (ft)	Imported soil required	Primary equipment
1........	Narrow trench	22	Yes	Land-based	—	4	No	Backhoe with loader, track dozer, excavator
2........	Wide trench	32	Yes	Sludge-based	—	5	No	Track loader, scraper track dozer
3........	Area fill mound	30	Yes	Sludge-based	3	1	Yes	Track loader, backhoe, track dozer, scraper, wheel loader
4........	Area fill layer	30	Yes	Sludge-based	0.5	1	Yes	Track dozer, scraper, grader, wheel loader
5........	Diked containment	25	Yes	Land-based	1	3	Yes	Dragline, track dozer, scraper
6........	Sludge/refuse mixture	20	Yes	Sludge-based	0.5	2	No	Track dozer, truck loader
7........	Sludge/soil mixture	20	No	Sludge-based	—	—	No	Tractor with disc, grader, track loader

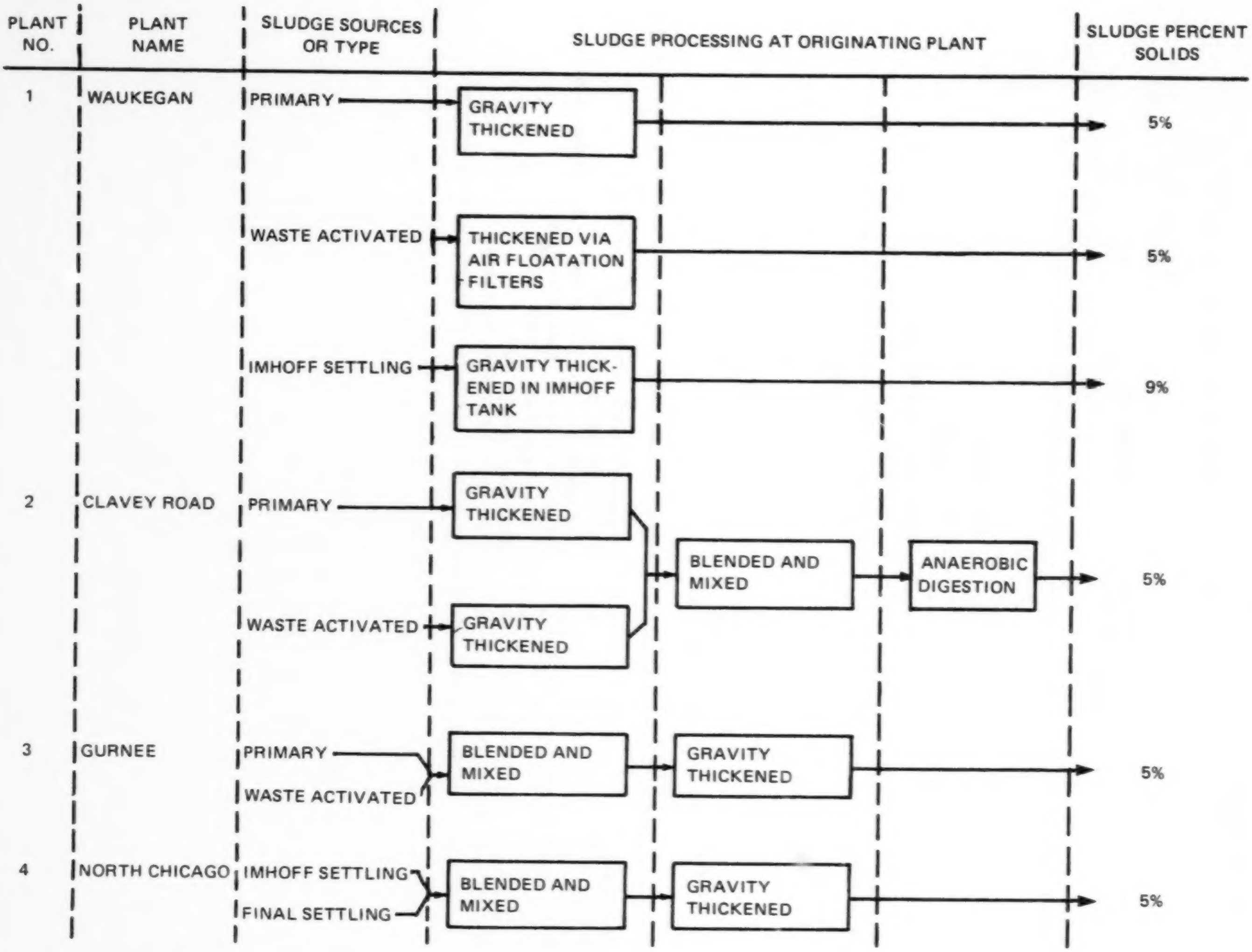
PLANT NO.
PLANT NAME
SLUDGE SOURCES OR TYPE
SLUDGE PROCESSING AT ORIGINATING PLANT
SLUDGE PERCENT SOLIDS
1
WAUKEGAN
PRIMARY
GRAVITY THICKENED
5%
WASTE ACTIVATED
THICKENED VIA AIR FLOATATION FILTERS
5%
IMHOFF SETTLING
GRAVITY THICKENED IN IMHOFF TANK
9%
2
CLAVEY ROAD
PRIMARY
GRAVITY THICKENED
WASTE ACTIVATED
GRAVITY THICKENED
BLENDED AND MIXED
ANAEROBIC DIGESTION
5%
3
GURNEE
PRIMARY
WASTE ACTIVATED
BLENDED AND MIXED
GRAVITY THICKENED
5%
4
NORTH CHICAGO
IMHOFF SETTLING
FINAL SETTLING
BLENDED AND MIXED
GRAVITY THICKENED
5%

Figure 10–16.—Sludge processing at originating plant.

selected for intensive investigation, based on the following considerations:

1. Short haul distance (10 mi or 16 km).
2. Availability of the land for purchase.
3. A large negative reaction from the public was not anticipated.

Accordingly, an option to purchase the land was acquired for this site, and hydrogeological investigations were begun to determine its environmental acceptability. After discussions with the Illinois Sanitary Water Board and the Illinois State Geological Survey regarding the data required to obtain preliminary approval of the landfill site, the District proceeded with the necessary soil borings and laboratory tests. A total of nine borings to a depth of up to 52 ft (16 m) were performed at the site.

By the end of 1970 the District contracted to have topographic maps made of the property. The maps of the 450 acre area were prepared at a scale of 1 in. = 1,000 ft (1 cm = 120 m) and 2 ft (0.6 m) contour intervals. These maps were provided to a consulting engineering firm that the District had contracted to prepare design and operation plans for the site.

Design

The design had to accommodate the following regulatory requirements of the Illinois State Environmental Protection Agency.

1. It had to follow the "Rules and Regulations for Refuse Disposal Sites and Facilities" (general operational requirements—no large impacts).
2. It was required that a 150 ft (46 m) buffer be placed between sludge deposits and the property

Table 10–13.—Details on sludge transported from originating plant to sludge processing unit at Waukegan

			Sludge generation rate			Transport to processing unit	
Plant number	Plant number	Sludge source	Lbs per day (dry solids weight)	Gallons per day (wet volume)	Days per week	Mode	Transport distance (miles)
1...............	Waukegan	Primary	13,530	32,446	5	8 in. diameter pipeline	<1
		Waste activated	15,409	25,177	5	8 in. diameter pipeline	<1
		Imhoff settling	13,530	27,038	5	8 in. diameter pipeline	<1
2...............	Clavey road	(All)	11,968	48,643	5	5,500 gal tank trucks	22
3...............	Gurnee	(All)	22,965	55,071	5	8 in. diameter pipeline	7.5
4...............	North Chicago	(All)	1,420	3,405	5	5,500 gal tank trucks	5
Total..			78,822	191,780			

1 lb = 0.454 kg.
1 gal/d = 3.785 L/d.
1 in. = 2.54 cm.
1 mi = 1.609 km.

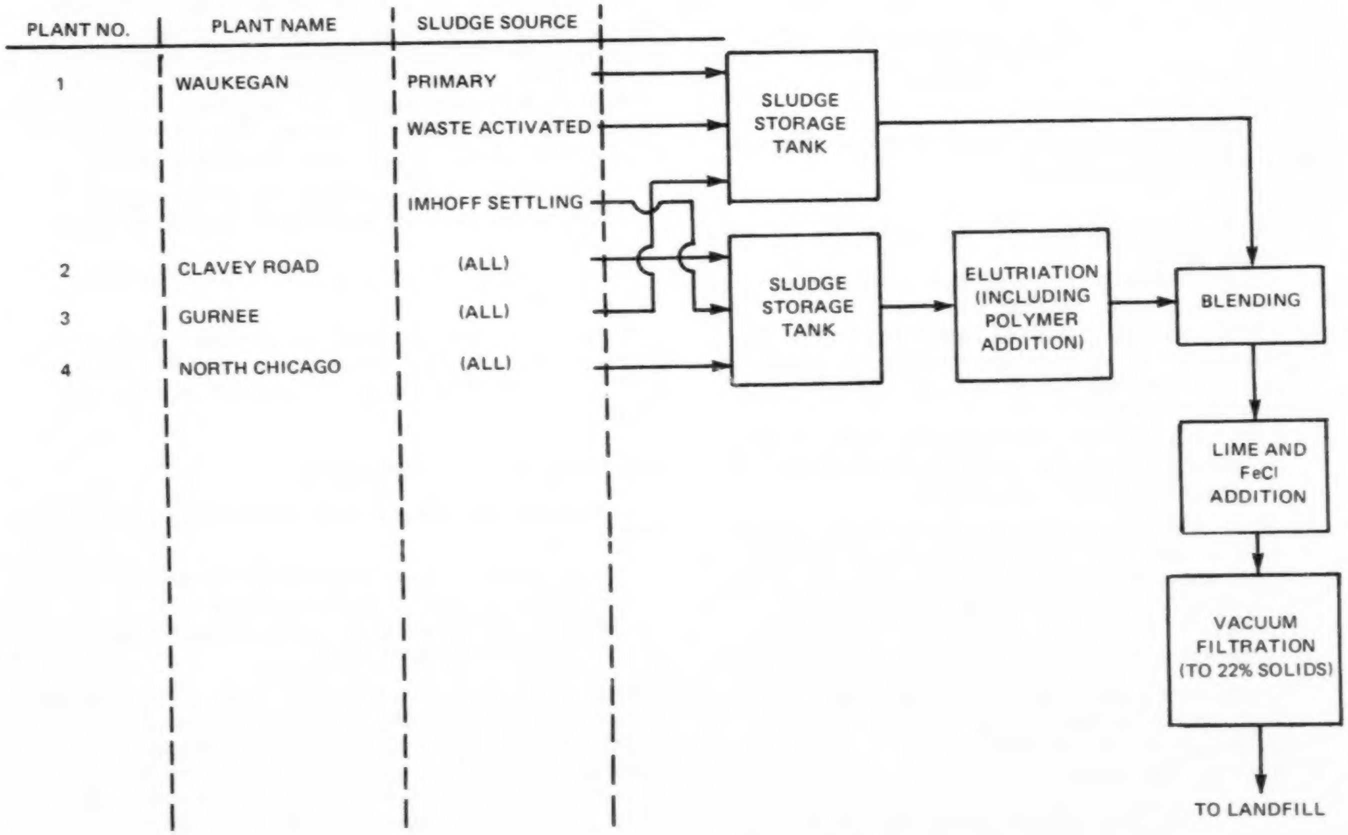
PLANT NO.
PLANT NAME
SLUDGE SOURCE
1
WAUKEGAN
PRIMARY
WASTE ACTIVATED
IMHOFF SETTLING
2
CLAVEY ROAD
(ALL)
3
GURNEE
(ALL)
4
NORTH CHICAGO
(ALL)
SLUDGE STORAGE TANK
SLUDGE STORAGE TANK
ELUTRIATION (INCLUDING POLYMER ADDITION)
BLENDING
LIME AND FeCl ADDITION
VACUUM FILTRATION (TO 22% SOLIDS)
TO LANDFILL

Figure 10–17.—Flow diagram: Sludge processing at Waukegan, Ill.

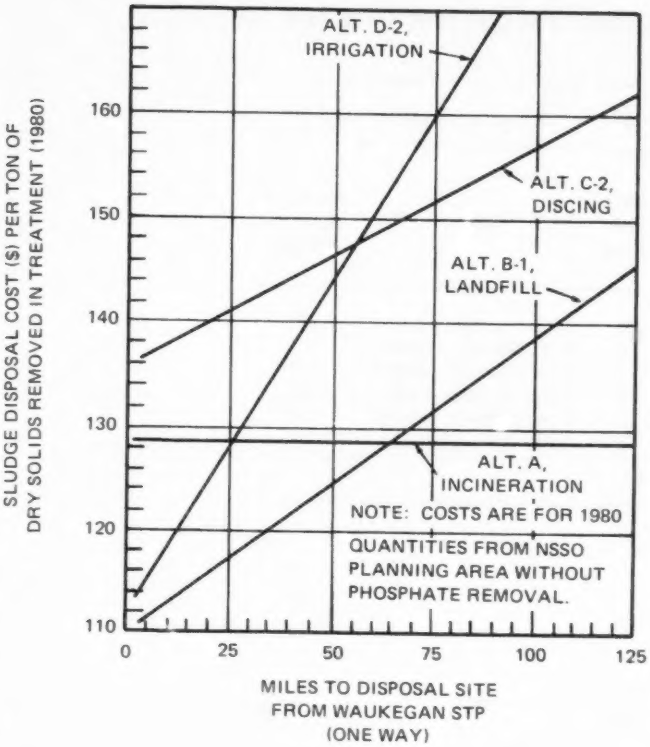

Figure 10–18.—Comparative costs of sludge disposal without phosphorus removal.

line of any residences and the center line of any county roads.

3. The site could accept only filter cake sludge conditioned with ferric chloride and lime.
4. It was required that groundwater monitoring wells be installed at state-approved locations. Monitoring for 22 contaminants was required annually; 5 parameters quarterly.
5. It was required that gas monitoring wells at state-approved locations be monitored for methane, carbon dioxide, nitrogen and oxygen.

Based on information obtained from borings, excavations were limited to a 15 to 20 ft (5 to 36 m) depth. At this depth, at least 20 ft (6 m) of silty clay with a low permeability would separate sludge deposits from groundwater.

Other design considerations included:

1. Relatively low solids sludge (22 percent).
2. Deep, well protected aquifer.
3. Stable soil for trench sidewalls.
4. Maximum site usage.

As a result of these considerations and the site characteristics, the District chose wide trenches as the disposal method.

In order to determine the stability and seepage characteristics of the soil, the District excavated two test pits on February 9 and 10, 1972.

Each pit was 24 ft by 50 ft (7 m by 15 m) at ground level. The slope of three sides was approximately 1:1, the fourth was 1 horizontal to 2 vertical, with a depth of 12 ft (4 m). All observations indicated that groundwater seepage was not excessive, and that the cuts were stable since no sloughing or caving of the banks was observed.

An application for a permit to install and operate a sanitary landfill, together with a detailed installation and operating plan, was then submitted to the Illinois State Environmental Protection Agency. The permit was issued on March 2, 1972. In September 1973, a contract was awarded by the District for preparation of the site in accordance with plans and specifications prepared by the consultant.

Public Participation

Public Interaction During Site Approval

Although when the District initially selected the site they anticipated little public resistance, protests began following reports of the proposed landfill operation in the media. However, the District performed detailed environmental impact investigations and prepared an operational plan designed to minimize impacts. The District worked closely with various regulatory authorities including:

1. Illinois State Environmental Protection Agency.
2. U.S. Department of Agriculture, Soil Conservation Service.
3. Lake County Illinois Soil and Water Conservation District.

These authorities reviewed and provided input to site plans and reports throughout the process and as a result of their support, the public reaction became less negative.

On-going Public Relations

Operational features designed to minimize public resistance were:

1. Application of cover over sludge throughout the day in warm weather to minimize odors.
2. Application of lime over sludge in haul vehicles at all times to minimize odors.

As a result, the only complaints received to date have been from a resident whose property is literally surrounded by the landfill. The resident's complaints are generally justified, and they have been constructive in nature. In general, they have centered on odors and noise; consequently, dumping and operating procedures have been restricted and currently run from 7 a.m. to 4 p.m.

Operation

Site preparation, sludge loading and transport, and the operating practices employed are discussed later. Operational considerations are presented below:

Sludge to groundwater	>10 ft (>3 m)
Soil cover thickness	5 ft (1.5 m)
Sludge application	9,100 yd^3/acre (17,200 m^3/ha)
Fill depth	14 ft (4 m)
Sludge exposure	<1 day
Total soil usage (sludge:soil)	1:0.6

Site Preparation

The existing on-site barn, silo, and minor outbuildings were demolished. The remaining farmhouse was used as an office. Structures for storing sludge and on-site equipment were constructed. A paved, all weather access road was constructed to within several hundred feet of the disposal area. Approaches to the disposal areas were covered with sand and gravel. A 6 ft (2 m) fence was provided for the area south of Ninth Street (figure 10–19). Lighting was installed around on-site structures and sewer, water, and telephone services were in place at the farmhouse.

Prior to excavating a trench the top 3 ft (0.9 m) of soil was stripped and stockpiled.

Sludge Loading and Transport

Sludge from the vacuum filter at the Waukegan sludge processing unit is transported via a conveyor belt that moves from end to end of a 30 yd^3 (23 m^3) open dump truck. Thus, sludge is spread evenly over the bed of the truck. There are five open-top dump trucks with sealed tailgates, and each makes about 5 trips to the landfill each day. The one-way haul distance is 10 mi (16 km) and the haul roads are compatible for truck traffic.

Operational Procedures

Individual cells 20 ft deep, 70 ft long and 22 ft wide (6 m deep, 21 m long, and 7 m wide) at the top are excavated by a large backhoe/excavator. Sidewalls are

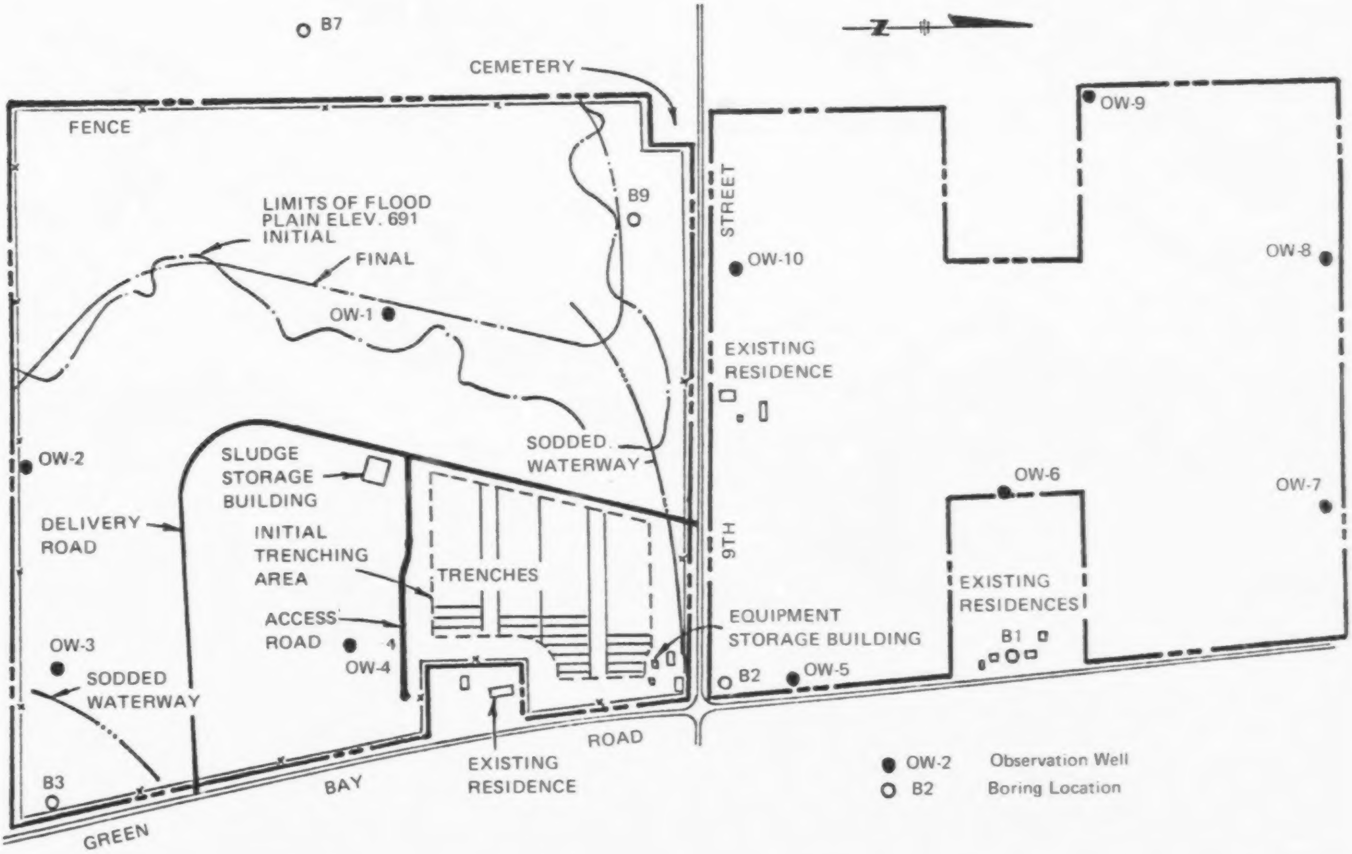
N
B7
CEMETERY
FENCE
B9
LIMITS OF FLOOD PLAIN ELEV. 691
INITIAL
FINAL
OW-1
9TH STREET
OW-9
OW-10
OW-8
EXISTING RESIDENCE
SODDED WATERWAY
OW-2
SLUDGE STORAGE BUILDING
OW-6
OW-7
DELIVERY ROAD
INITIAL TRENCHING AREA
TRENCHES
EXISTING RESIDENCES
ACCESS ROAD
OW-4
EQUIPMENT STORAGE BUILDING
B1
OW-3
SODDED WATERWAY
B2
OW-5
ROAD
EXISTING RESIDENCE
BAY
GREEN
B3
● OW-2 Observation Well
○ B2 Boring Location

Figure 10–19.—Site operating plant, Waukegan, Ill.

straight on all but one side; the 70 ft (21 m) length on the side where dumping is done has a 6 ft (2 m) wide step halfway down for added sidewall stability. Thus, the bottom cell width is 16 ft (5 m). Consecutive cells are constructed with the 70 ft (21 m) sides parallel. Twenty ft (6 m) of solid ground is maintained between the parallel cells and consecutive cells proceed in a line to form a single trench (figure 10–20). After completion of one line of cells, a second line is begun (as shown in figure 10–19) to the side of the first line. Five ft (2 m) of solid ground is maintained between adjacent trenches. The trenches are graded so that leachate can be collected at one end of the trench and returned to the Waukegan plant for treatment. Haul vehicles back up on prepared sand and gravel access roads to the long sides of each cell, and sludge is dumped by the trucks in progression from one end of the 70 ft (21 m) length to the other.

Usually the consistency of the sludge is such that it flows out to an even grade inside each cell. However, the bucket of the backhoe/excavator is used to spread the sludge evenly at the end of the day. One day's sludge usually accumulates to a 2 ft (0.6 m) thickness. Filling proceeds to within 2 ft (0.6 m) of the surface before proceeding to a new cell.

At the end of each day, a 6 to 8 in. (15 to 20 cm) soil cover is applied over the sludge. After filling has proceeded to within 2 ft (0.6 m) of the subsurface (usually at the end of a week), a 5 ft (2 m) cap of topsoil cover (previously stockpiled) is applied to 3 ft (0.9 m) above grade by the backhoe. After initial settlement the cell is final graded and compacted with small bulldozers (including a D–3 and a D–5). Additional operational characteristics are detailed below.

The equipment and personnel at the site are as follows:

Equipment:

1 – Backhoe/excavator (Northwest with 1.5 yd^3 bucket).
1 – Front-end loader (Hough with 2 yd^3 bucket).
1 – Bulldozer (Caterpillar D–3).
1 – Bulldozer (Caterpillar D–5)

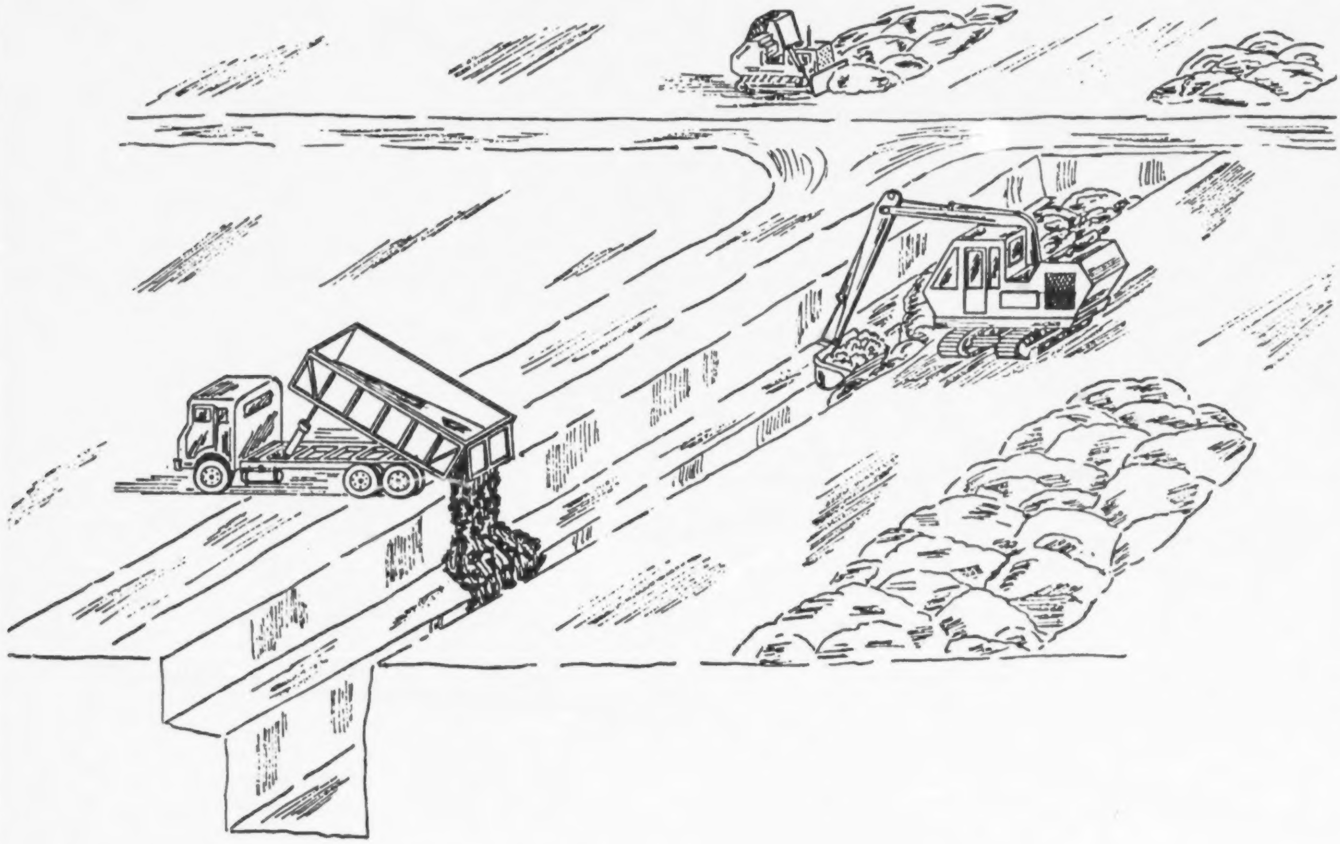

Figure 10–20.—Wide trench operation, Waukegan, Ill.

Personnel:
1 – Superintendent.
3 – Equipment operators.
1 – Laborer.

Problems encountered during the operation of the landfill, together with controls are detailed below:

1. Problem: Freezing temperatures make excavation of cells and placement of stockpiled cover impossible. Snow and rain make access to cells by haul vehicles and site operation by equipment difficult.

   Control: During inclement weather, soil is stockpiled on the site inside a sludge storage building accessible via paved roads. This building is a steel frame structure 50 ft by 50 ft by 30 ft (15 m by 15 m by 9 m) high. It is constructed on a concrete slab with concrete sidewalls extending 3 ft (0.9 m) high. A trench drain is located in the middle of this slab to collect sludge moisture. This leachate is directed to an underground 10,000 gal (37,850 l) storage tank. Leachate is pumped out of the tank as necessary and transported via tank truck to the Waukegan Plant for treatment. In poor weather, all sludge delivered to the site is dumped into the building which prevents the addition of moisture from precipitation and controls odors. When weather improves, the sludge is loaded back into dump trucks with front-end loaders and hauled to the cells.

2. Problem: Soil runoff from denuded fill areas.

   Control: Fill areas are seeded with grasses soon after completion. All on-site drainage is channeled through sod-lined ditches to a collection pond.

3. Problem: Odors from sludge during transport, from uncovered sludge in cells during warm weather, from sludge spills, and from equipment.

   Control: Initially sludge transport was to be in dump truck trailers covered with tarpaulins for odor control. However, this caused operational difficulties and transport is now accomplished in open-top trucks. However, after loading, the sludge is covered with a layer of lime for odor control while in transit. In warm weather, sludge in the cells is covered during the day as well as at the end of the day. Lime is sprinkled over any sludge spills. The backhoe bucket (which comes into contact with sludge) is buried in soil at the end of the day to minimize odors.

4. Problem: Mud from site is tracked onto adjoining roadways by haul vehicles.

   Control: A washrack is located at the Waukegan Sludge Processing Unit. It is used to clean haul vehicles in wet weather.

5. Problem: Noise of haul vehicles and on-site equipment bothers near-site residents.

   Control: Per agreement with nearby residents, hauling and operation is confined to between 7 a.m. and 4 p.m.

Figures 10–21 through 10–24 illustrate the equipment and operations at the Waukegan site.

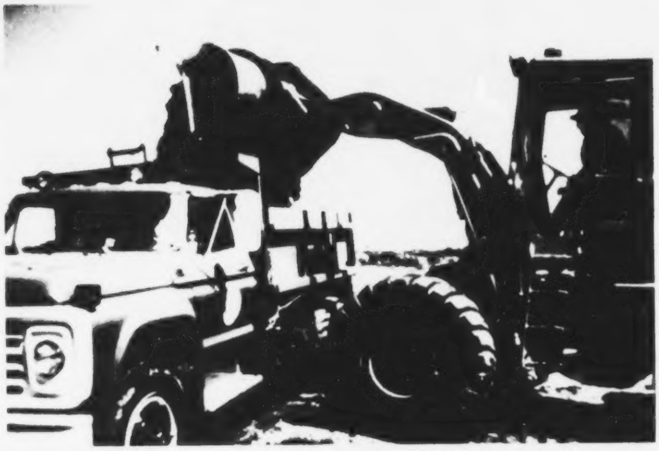

Figure 10–21.—Stockpiling soil, Waukegan, Ill.

Figure 10–22.—Unloading sludge into wide trenches, Waukegan, Ill.

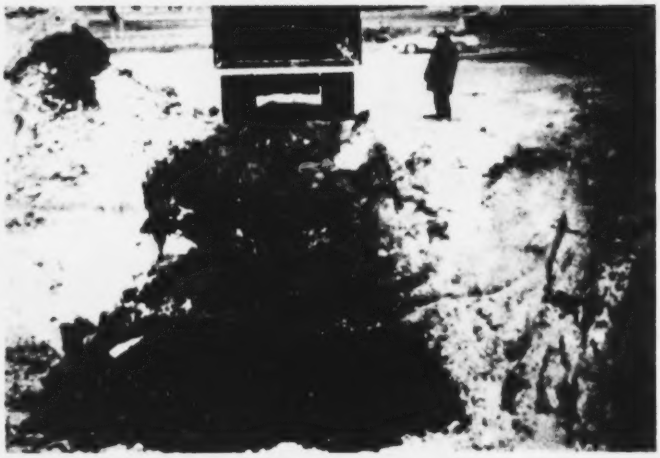

Figure 10–23.—Placing interim cover, Waukegan, Ill.

Figure 10–24.—Placing final cover, Waukegan, Ill.

Monitoring

Background samples were taken from all wells prior to initiating operations so that baseline conditions could be established. Subsequent monitoring has not detected any contamination of groundwater in on-site wells nor has water from the collection pond and drainage ditches contaminated surface waters. Establishing initial conditions proved valuable since one of the local potable wells showed contamination that could have been attributed to sludge disposal but was known to have preceded disposal operations as a result of initial tests.

The number, location, and function of the monitoring wells were established in conjunction with the Illinois State Environmental Protection Agency. Figure 10–19 illustrates the location of the wells and tables 10–14 and 10–15 detail the wells and monitoring parameters.

Costs

A breakdown of the on-site costs reveals that the cost per dry ton of sludge was $14.56 ($16.05/Mg). The costs were calculated in the following manner: first capital expenditures were divided by the total amount of sludge received over the life of the site; next operating costs were divided by the amount of sludge received for the period considered (6 months in this case); finally the figures were added to arrive at the total cost per unit of sludge (excluding hauling costs). The intensive use of the available land contributed to this relatively low figure. Following is breakdown of the costs by category.

	Cost	*Unit cost ($/dry ton sludge)*
Site capital costs		
Land	$450,000	$2.25
Monitoring wells	12,000	0.06
Site preparation	328,000	1.64
Total capital cost	790,000	3.95
Site operating cost (October 1977 through March 1978)		
Labor	18,200	3.64
Equipment depreciation	16,450	3.29
Administration	7,300	1.46
Maintenance	6,850	1.37
Laboratory	1,450	0.29
Fuel	1,250	0.25
Operating materials & supplies	900	0.18
Miscellaneous	650	0.13
Total site operating cost	53,050	10.61
Total cost	—	14.56

Hauling costs have not been included in the total cost.

DESIGN EXAMPLE

Introduction

The design of a sludge landfill is highly dependent upon many sludge characteristics and site conditions, such as percent solids, climate, soil, topography, and others. Consequently, no single design example can be universal. However, an example can be illustrative of the design and operating procedures which have been recommended in previous chapters.

The approach here is to present sludge characteristics and site conditions as given design data. The design process then proceeds to (1) select the landfill method,

Table 10–14.—Summary of groundwater and gas wells and surface water stations

Monitoring type	Well/station number	Relation to fill		Well specifications		
		Location (up- or down-gradient)	Distance (ft)	Total depth (ft)	Depth below groundwater (ft)	Drill rig used
Groundwater	OW-1	Down-gradient	200	30	5	Auger
	OW-2	Down-gradient	100	30	5	Auger
	OW-3	Up-gradient	100	30	5	Auger
	OW-4	Up-gradient	20	30	5	Auger
	OW-5	Up-gradient	100	30	5	Auger
	OW-6	Up-gradient	100	30	5	Auger
	OW-7	Up-gradient	100	30	5	Auger
	OW-8	Down-gradient	100	30	5	Auger
	OW-9	Down-gradient	100	30	5	Auger
	OW-10	Down-gradient	100	30	5	Auger
	5 potable wells	Down-gradient	>1/2 mi	—	—	—
Gas	Gas well 1	In-sludge	—	—	—	—
Leachate	Sludge cell	—	—	—	—	—
	Tank under sludge storage building	—	—	—	—	—
Surface water	Runoff pond	—	—	—	—	—
	Drainage ditches	—	—	—	—	—

1 ft = 0.305 m.

Table 10–15.—Sampling and analytical program

Monitoring type	Well/station number	Sample collection technique	Analyses		
			Parameter(s)	Total times to date	Frequency
Groundwater	OW-1 OW-2 OW-3 OW-4 OW-5 OW-6 OW-7 OW-8 OW-9 OW-10 5 potable wells	10 ft length of 1-in. diameter PVC pipe, fitted with polyethylene foot valve on bottom	22 parameters including metals as dictated by State EPA	3	1 × per yr
Gas	Gas well 1	Gas cylinder	CO_2, O_2, N_2, CH_4, COS, H_2S, SO_2	About 20	2 × per mo
Leachate	Sludge cell Tank under sludge storage building	Grab sample	Heavy metals COD, BOD, TOC, pH, NH_3, NO_3	About 20	Irregularly
Surface water	Runoff pond Drainage ditches	Grab sample	Fecal coliform	About 20	Irregularly

(2) compute the landfill dimensions, (3) prepare site development plans, (4) determine equipment and personnel requirements, (5) develop operational procedures.

It should be noted that the scope of this chapter is confined to design only; i.e., it is assumed that the site in the design example has already been selected. It should also be noted that the design described in this Chapter is somewhat preliminary in nature. A final design should contain more detail and address other design considerations (such as sediment and erosion controls, roads, leachate controls, etc.) which are not addressed herein.

Statement of Problem

The problem is to design a sludge-only landfill at the location of a pre-selected site. The landfill is to receive sludge from an existing municipal wastewater treatment plant with secondary treatment. The recommended design must be the most cost-effective, well-suited for local conditions, and in full compliance with regulatory constraints.

Design Data

The following information is included as given design data and will be useful in executing the subsequent design.

Plant Description

The wastewater treatment plant is a modern secondary treatment facility. Further information on the facility is as follows:

1. Service population equivalent = 500,000.
2. Average flow = 50 Mgal/d (190 ML/d).
3. Industrial inflow—10 percent of total inflow.
4. Wastewater treatment processes:
   - Bar screen separation.
   - Aerated grit tanks.
   - Primary settling tanks.
   - Secondary aeration tanks.
   - Secondary settling tanks.
   - Sand filters.
   - Chlorine contact tanks.

Sludge Characteristics

Sludge is primarily generated from two sources (the primary and secondary clarifiers). The sludge is then mixed, stabilized with lime, and dewatered. A more complete description is as follows:

1. Sludge sources.
   - Primary settling tanks.
   - Secondary settling tanks.
2. Sludge treatment.
   - Gravity thickening.
   - Mixing.
   - Lime addition.
   - Pressure filtration.
3. Sludge solids content = 30 percent.
4. Sludge quantity (dry weight basis) = 48 tons/day (44 Mg/day).

Climate

Significant factors impacting on sludge landfilling are listed below:

1. Precipitation = 50 in./yr (127 cm/yr).
2. Evaporation = 30 in./yr (76 cm/yr).
3. Mean temperature = 32° F (0° C) for 40 days/yr.

As shown, the climate is relatively mild with cold temperatures prevailing only slightly more than one month per year. Precipitation is high and exceeds evaporation by 20 in./yr (51 cm/yr).

General Site Description

Preliminary data were collected during the site selection process. It is summarized below:

1. Depth to groundwater = 12 ft (3.7 m).
2. Depth to bedrocks = 7 ft (2.1 m).
3. Size of property = 375 acres (152 ha).
4. Property line frontage:
   - 5,200 ft (1,580 m) along county road.
   - 4,700 ft (1,430 m) along residences.
   - 4,600 ft (1,400 m) along grazing land.
   - 1,200 ft (370 m) along woodland.
5. Slopes: Uniform slope of approximately 5 percent.
6. Vegetation:
   - 225 acres (91 ha) of woodland.
   - 150 acres (60 ha) of grassland.
7. Surface water: None on site.

A plan view of the site is presented in figure 10–25. As shown, the site has good access along a county road. The site is located in a moderately developed residential area and abuts residences. Approximately 60 percent of the site is covered with woodland. The balance of the property was recently used for grazing and remains grass-covered.

Soil Description

Eight test borings were performed on the site to determine subsurface conditions. These are located as shown in figure 10–25. Subsurface conditions generally are similar at the boring locations and can be summarized as follows:

Depth	*Type*	*Permeability*
0–2 ft (0–0.6 m)	Top soil	High
2–9 ft (0.6–2.1 m)	Silt loam	Medium
>9 ft (>2.1 m)	Soft shale	Low

Design

Landfilling Method

Table 10–9 should be consulted for a reference. As shown, when a trench design is selected and the solids

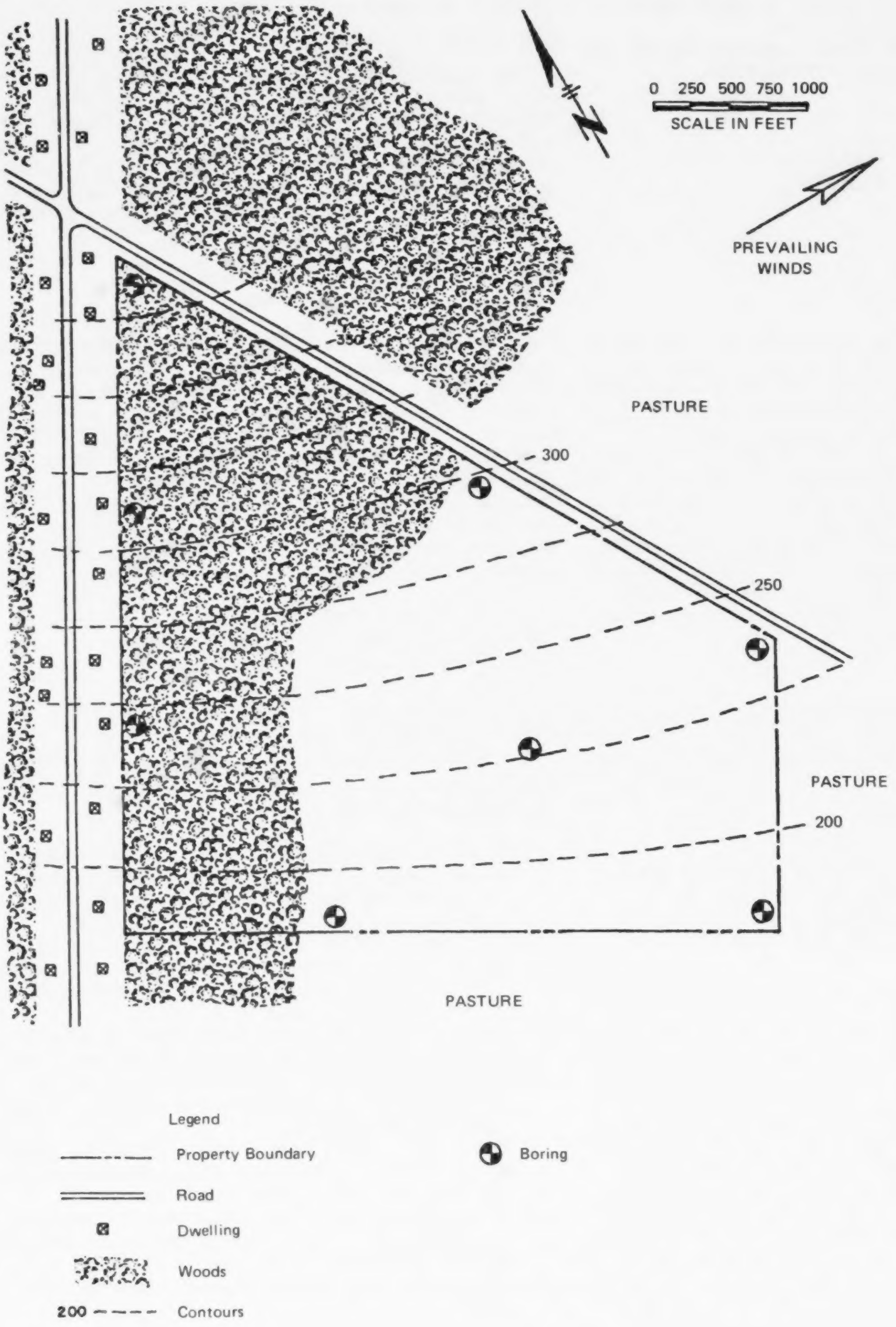
0 250 500 750 1000
SCALE IN FEET
PREVAILING WINDS
350
PASTURE
300
250
PASTURE
200
PASTURE
Legend
Property Boundary
Boring
Road
Dwelling
Woods
200
Contours

Figure 10–25.—Site base map.

content is approximately 32 percent, a design similar to Scheme No. 6 should be implemented.

Scheme No. 6 is a wide trench operation and typically employs the following design characteristics:

1. Trench width = 60 ft (18 m).
2. Trench depth = 8 ft (2.4 m).
3. Trench length = 600 ft (18.3 m).
4. Trench spacing = 30 ft (9.1 m).
5. Fill depth = 4 ft (1.2 m).
6. Soil used for bulking = No.
7. Soil used for cover = Yes.
8. Cover thickness = 5 ft (1.5 m).
9. Off-site soil needed = No.

Scheme No. 6 allows haul vehicles to enter the trench and dump the sludge load directly onto the floor of the trench in 4 ft (1.2 m) high piles. The high solids content of the sludge (30 percent) allows the sludge to be dumped in piles without significant slumping.

Scheme Nos. 1 through 5 were not selected because these operations require that sludge be dumped into the trench from atop the trench sidewall. The consistency of the low solids sludge in these operations allows the sludge to spread out evenly in the trench. If high solid sludge available in this example were dumped from atop a trench, it would accumulate at the dumping location and equipment would be needed to spread the sludge.

Design Dimensions

The width and length of individual trenches shown above is for medium size sludge landfill operations. At 48 dry tons/day (55 Mg/day) of sludge generation, this site falls into this category. Thus,

1. Trench width = 60 ft (18 m).
2. Trench length = 600 ft (183 m).

Trench depth is normally 8 ft (2.4 m) for this operational scheme. However, shale bedrock is at a 9 ft (2.1 m) depth. Accordingly, excavation should proceed no deeper than 7 ft (2.1 m) to allow sufficient soil cover over the bedrock.

3. Trench depth = 7 ft (2.1 m).

Groundwater is at a depth of 12 ft (3.7 m) below the ground surface. A 5 ft (1.5 m) separation of tight weathered shale rocks and soils was deemed adequate to protect the groundwater.

As a rule of thumb 1 to 1-1/2 ft (0.3 to 0.5 m) of solid ground must be maintained between trenches for every 1 ft (0.3 m) of trench depth for the purposes of trench sidewall stability. As shown in table 10–9, however, a trench spacing of 30 ft (9.1 m) is recommended for Scheme No. 6, despite a trench depth of only 7 ft (2.1 m). The trench spacing is large due to the placement of large soil stockpiles between trenches. In addition, bulldozers applying cover material need sufficient space to maneuver in this area. Thus,

4. Trench spacing = 30 ft (9.1 m).

The sludge fill depth suggested by Scheme No. 6 if 4 ft (1.2 m). Since sludge is dumped from haul vehicles based on the floor of the trench, fill depths higher than 4 ft (12 m) are not practical. The high solids content of the sludge means that the sludge has sufficient stability to ensure minimal slumping without the addition of soil. Accordingly, a sludge fill depth of 4 ft (1.2 m) is practical. Thus,

5. Fill depth = 4 ft (1.2 m).
6. Soil used for bulking = No.

In order to cover the 60 ft (18 m) wide trench fill, soil must be applied by equipment moving out over the sludge. A thick 5 ft (1.5 m) mantle of soil should be adequate to support the equipment over the 4 ft (1.2 m) layer of sludge. Soil can be taken from the 7 ft (2.1 m) deep trench in which the sludge is landfilled. The cover should consist of 3 ft (0.9 m) of soil to the top of the trench, and an additional 2 ft (0.6 m) above grade to account for future settlement. Some soil will still be available after this initial cover application for future regrading needed for additional settlement. Thus,

7. Soil used for cover = Yes.
8. Cover thickness = 5 ft (1.5 m).
9. Off-site soil needed = No.

Site Development

Site development will be in accordance with the Development Plan shown in figure 10–26. Development features included the following:

1. A 500 ft (150 m) wooded buffer should be maintained between the sludge fill area and the residences. A 200 ft (60 m) buffer should be maintained around the balance of the property.
2. Trenches should be oriented with their long axes parallel to the topographic contours. In this manner, trench bottoms will be evenly graded and sludge will not flow to one end.
3. Although 30 ft (9.1 m) of solid ground is maintained between the long sides of adjacent trenches, 100 ft (30 m) of solid ground should be maintained between the short sides of adjacent trenches for passage by haul vehicles.
4. Storm water runoff from fill areas should be collected by cutoff trenches along the southwestern property line and diverted to a siltation pond.
5. In accordance with State regulations and engineering judgement one groundwater monitoring well was located up-gradient from fill areas and three monitoring wells were located down-gradient from fill area.

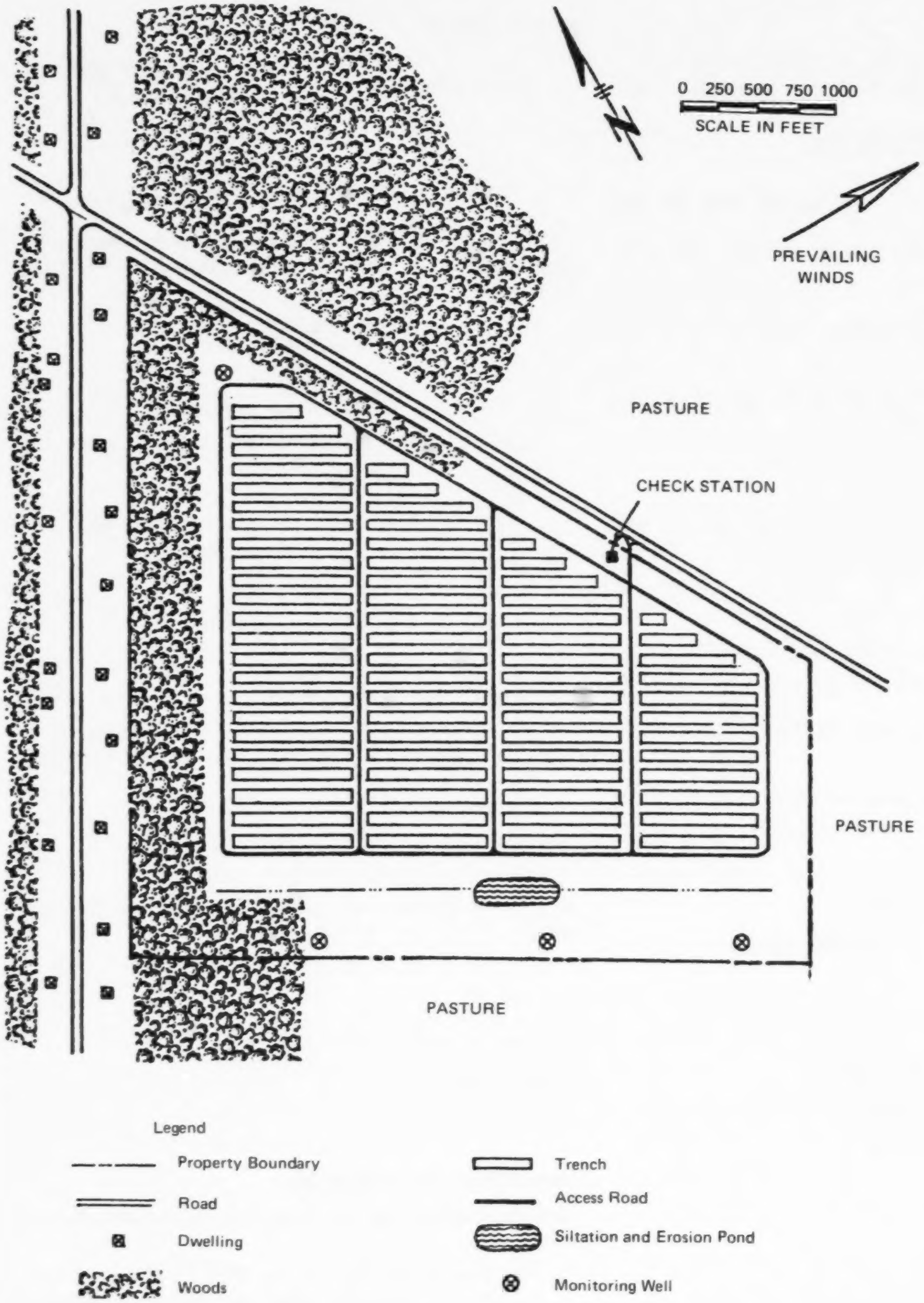
N
0 250 500 750 1000
SCALE IN FEET
PREVAILING WINDS
PASTURE
CHECK STATION
PASTURE
PASTURE
Legend
Property Boundary
Road
Dwelling
Woods
Trench
Access Road
Siltation and Erosion Pond
Monitoring Well

Figure 10–26.—Site development plan.

Calculations

Given a sludge quantity of 48 dry tons/day (44 Mg/day) a calculation can be made of the sludge quantity on a wet weight basis:

$$\frac{\text{(dry weight)}}{\text{(percent solids)}} = \frac{\text{48 dry tons per day}}{0.30}$$

$$= \text{160 wet tons per day}$$

A calculation can also be made of the wet volume of the sludge:

$$\frac{\text{weight of solids}}{\text{density of solids}} = \text{volume of solids}$$

$$\frac{\text{(48 dry tons per day)(2,000 lbs per ton)}}{(80\ \text{lbs/ft}^3)(27\ \text{ft}^3/\text{yd}^3)} = 44\ \text{yd}^3 \text{ of solids}$$

$$\frac{\text{weight of water}}{\text{density of water}}$$

$$= \frac{\text{(0.70)(160 wet tons per day)(2,000 lbs per ton)}}{(62.4\ \text{lbs/ft}^3)(27\ \text{ft}^3/\text{yd}^3)}$$

$$= 132\ \text{yd}^3 \text{ of water}$$

$$\text{total volume} = \text{solids volume} + \text{water volume}$$

$$= 44\ \text{yd}^3 + 132\ \text{yd}^3 = 176\ \text{yd}^3$$

A calculation can then be made of the landfill capacity, as follows:

$$\text{capacity per acre} = \frac{\text{cubic yards of sludge per trench}}{\text{area of land consumed per trench}}$$

where:

cubic yards of sludge per trench

$$= \text{(trench width)(trench length)(fill depth)}$$

$$= \frac{(60\ \text{ft})(600\ \text{ft})(4\ \text{ft})}{27\ \text{ft}^3/\text{yd}^3}$$

$$= 5{,}333\ \text{yd}^3$$

area of land consumed per trench

$$= \text{(trench width + spacing)(trench length + spacing)}$$

$$= (60\ \text{ft} + 30\ \text{ft})(600\ \text{ft} + 100\ \text{ft})$$

$$= (90\ \text{ft})(700\ \text{ft})$$

$$= 63{,}600\ \text{ft}^2$$

$$= 1.45\ \text{acres}$$

$$\text{capacity per acre} = \frac{5{,}333\ \text{yd}^3}{1.45\ \text{acres}} = 3{,}678\ \text{yd}^3/\text{acre}$$

The land fill's land utilization rate can then be calculated as follows:

$$\text{land utilization rate} = \frac{\text{sludge volume per day}}{\text{capacity per acre}}$$

$$= \frac{176\ \text{yd}^3/\text{day}}{3{,}678\ \text{yd}^3/\text{acre}}$$

$$= 0.0479\ \text{acres per day}$$

The site life can then be calculated since there are approximately 140 acres of area available for filling at the landfill.

$$\text{site life} = \frac{\text{site size}}{\text{land utilization rate}}$$

$$= \frac{140\ \text{acres}}{0.0479\ \text{acres per day}}$$

$$= 2{,}923\ \text{days} \div 365\ \text{days per year}$$

$$= 8.0\ \text{years}$$

$$\text{trench life} = \frac{\text{gross trench acreage per trench}}{\text{fill acreage per day}}$$

$$= \frac{1.45\ \text{acres}}{0.0479\ \text{acres per day}}$$

$$= 30\ \text{days}$$

Equipment and Personnel

Using the equipment selection matrix, the following pieces of equipment would be utilized for this operation:

Description	*Quantity*
Track dozer	1
Scraper (self-propelled)	1
Total	2

The following personnel would be utilized for this operation:

Description	*Quantity*
Dozer operator	1
Scraper operator (as a fill-in one of the operators will work as needed as a laborer or check station attendant, or cover during vacation periods)	1
Total	2

Operational Procedures

Site preparation should consist of the following procedures:

1. The area to be filled in the next 6 months should be cleared using the dozer and the debris disposed of on-site by burial and or producing wood chips. The scraper should excavate trenches to prescribed

dimensions and stockpile the excavated material along the long sides of the excavated trench.

2. Trench excavation should be completed for each trench before sludge filling has been initiated at the preceding trench.
3. Excavation of trenches should proceed in each row starting farthest away from the gate and proceeding toward it.
4. Two trenches should be excavated near the entrance to the site for use during inclement weather.

Sludge unloading should consist of the following procedures:

1. Haul vehicles should stop at the check station upon entry to the site to register and to receive dumping instructions if the attendant is not at the working area.
2. The haul vehicles should then proceed toward the designated trench, enter the trench at the ramp from the short side, and dump the sludge at the far end in 4 ft high piles, as shown in figure 10–27.

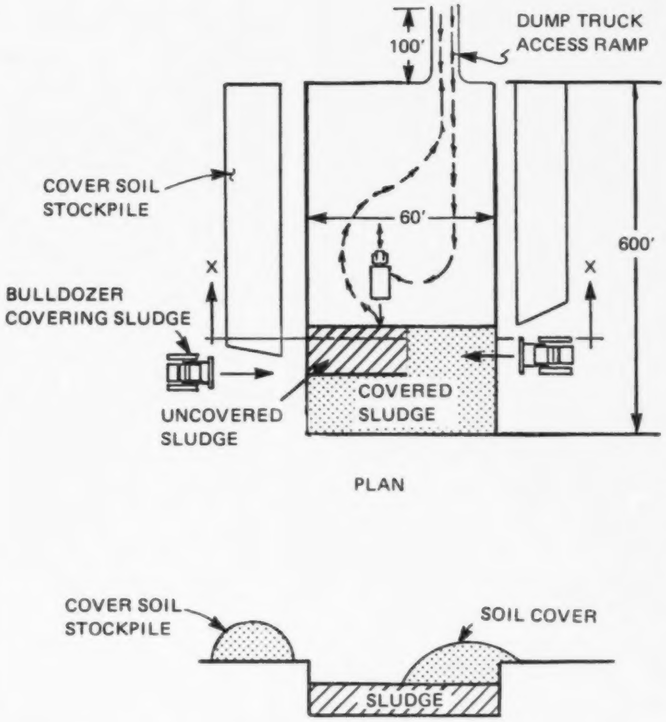

Figure 10–27.—Trench cross-section.

Sludge covering should consist of the following procedures:

1. At the end of each day, the bulldozer applies cover material from both sides of the trench over the sludge in a 5 ft thick application to 2 ft above grade.
2. End-of-the-day cover application should be adequate for odor control due to the stabilized nature of the sludge and the wooded buffers separating fill areas from residences. However, periodic application of cover several times during the day may be required if odor can be detected off-site.
3. Approximately one month after the completion of each trench, bulldozers should regrade completed fill areas to account for settlement and periodically thereafter if required.
4. The completed covered fill and adjoining areas where soil had been stockpiled should be sealed with grass after final cover regrading (1 month after completing the fill assuming weather conditions permit; e.g., during the three months of colder weather planting will not be effective).

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